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VTOL TRANSPORT AIRCRAFT

Comparative Study

FINAL SUMMARY REPORT
VERTOL REPORT NO. R-85

VERTOL Aircraft Corporation

formerly - Piasecki Helicopter Corporation

[redacted]

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Comparative Study of Various Types of
VTOL Transport Aircraft

FINAL SUMMARY REPORT R-85

Vertol Aircraft Corporation   Morton, Pennsylvania

ONR   **ARMY**

A Combined

Research and Development Program

Contract NONR 1681(00)

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JULY 13, 1956

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I. SUMMARY

In May 1955, Vertol Aircraft Corporation received Contract 1681(00) from the Office of Naval Research, Air Branch, under the sponsorship of the Army Transportation Corps to undertake a broad comparative study of vertical take-off and landing aircraft suitable for military transport missions in the period 1960 to 1965. This report presents a summary of the work performed during the study period.

A. Requirements

In the past several years, the development of low specific weight power plants and of successful methods of generating high lift, has resulted in many proposed design configurations of aircraft capable of vertical take-offs and landings and also capable of much higher flying speeds than contemporary helicopters.

In order to establish the relative competitive position of these many proposed configurations, a broad comparative parametric study was made for a transport aircraft capable of accomplishing the following specified missions:

1.	Payload	8000 lb. out - 4000 lb. back
2.	Take-off	Vertical
3.	Cabin Size	8' x 9' x *
4.	Cargo	35 Infantry troops or equivalent vehicles
5.	T.O. Conditions	Pressure altitude 6000 ft. at 95°F
6.	Runway Surface	Friction coefficient μ = .2; UCI = 15 **
7.	Cruise Speed	300 MPH
8.	Flight Profile	20% of radius adjacent to target at S.L.
9.	Landing	Vertical
10.	Radius of Action	425 Statute miles

* As required to accommodate 35 troops.
** Applicable to the case of running take-off at overload gross weight.

Furthermore, it was specified the aircraft must remain controllable with one engine inoperative and be able to make a "controlled crash" landing.

The study was confined to types which offer reasonable technical promise of becoming operationally available within the next 5 to 10 years. Therefore, technical data, such as power plant performance and weights, structural weights, etc. were extrapolated to 1962 state of art.

B. Scope

In order to investigate and categorize the many VTOL design concepts, it was decided to consider cruise speed as a variable. With cruise speed as a variable, the entire spectrum of VTOL aircraft, from helicopters to direct-lift turbojet aircraft, can be evaluated.

Consequently, for the initial study, all possible design concepts for VTOL transports were included. The various configurations included in this analysis are tabulated below:

1. Rotary - Wing Concepts

Configurations

a. Conventional Tandem Rotor Helicopter
b. Tandem Rotor Helicopter equipped with BLC Rotors
c. Compound Helicopter
d. Retractoplane

2. Fixed - Wing Concepts

a. Tilt Wing
b. Deflected Thrust
c. Vectored-Lift
d. Vertodyne (Breguet-Kappus)
e. Special Hovering Turbojet
f. Tilting Ducted Propeller
g. Aerodyne

Of the many VTOL transport concepts investigated, the following six designs appeared to be the most suitable for fulfilling the mission requirements at cruising speeds of 300 mph or greater:

(1) Tilt-Wing Propeller
(2) Tilting Ducted Propeller
(3) Vectored-Lift
(4) Special Hovering Turbojet
(5) Vertodyne (Breguet-Kappus)
(6) Aerodyne

In keeping with the intent of the subject contract it was decided that once again the broad approach should be taken. Consequently, these six configurations were analyzed to determine the required gross weight to meet the specified mission. In order to evaluate these six configurations, on a comparative basis, the following basic design considerations were established:

3. Dimensional Data

   a. Cargo compartment - 8' x 9' -3" x 35' long. The compartment is large enough to accommodate 35 troops arranged in two rows; one row along each side of the fuselage facing inward. Three standard Army jeeps, four bob-cat jeeps, and numerous other Army vehicles may be loaded internally.

   b. The loading ramp angle with respect to the ground line has been kept at 13 degrees (per HIAD).

   c. The truck bed loading height has been kept at 46 inches.

4. Positive Control in Hovering and Slow Speed Flight

   a. Interconnected propellers are provided to insure control during an engine-out condition.

   b. Auxiliary devices are provided for positive effective pitch and yaw control.

5. Operation from Unprepared Fields

   a. Wherever possible, engines are located so that the hot exhaust gases do not constitute an operational hazard.

6. Engine Availability

   a. Only engines which will be available in the period 1956-1960 are considered.

On the above basis the final design configuration of each of these concepts has been established and aircraft obtained in this way were not much different from those visualized in the preliminary analysis (Ref. 5). The sole exception to this rule was represented by the Aerodyne concept where due to the loading and mission requirements it was necessary to deviate from the "cigar-shape" structure visualized by the inventor and develop a configuration consisting of a central fuselage and two lift-thrust generators attached to the fuselage. Although the design solution is different from the original Aerodyne, the basic principle of using the same thrust generator throughout all regimes of flight (from hovering to V_{max}) as a source of lift as well as forward propulsion is maintained. Nevertheless, because of the fact that the proposed design solution, although based on the Aerodyne principle, differs from its design concept, the aircraft presented in this study will be referred to as the "Vectodyne."

The results of these design studies indicate that the spectrum of weights range from the Tilt Wing Propeller (lightest) to the Vectcdyne (heaviest). From a weight and performance viewpoint, the Tilt Wing Propeller and Tilting Ducted Fan are very nearly the same. The Vectored Lift concept is substantially heavier due to its relatively lower efficiency in vertical flight. The Special Hovering Turbojet, Vertodyne and Vectodyne are competitive for VTOL aircraft capable of jet speeds.

Upon reviewing the results of these design studies, it was apparent that the Tilt Wing Propeller aircraft was the optimum VTOL concept for cruising speeds of 300 to 350 mph while the Vertodyne appeared most suitable at higher cruising speeds. These two configurations, consequently, were selected for further analysis. Due to the limited scope of the subject contract, only some of the problems peculiar to each configuration were investigated.

For the Tilt Wing Propeller aircraft, a study was made of the propeller aerodynamics in order to determine the compromises that may be involved for achieving required thrust for hovering and forward flight. Transition from hovering to forward flight and the reverse procedure and engine-out descent analyses were also made. The potential of this configuration for STO (short take-off) operation was analyzed. To assure proper wing weights, a stress analysis of a tilting wing was undertaken. Finally, an investigation was made to determine the effect of hovering ceiling, cruise altitude and hovering duration on the optimum size of the aircraft.

For the Vertodyne aircraft, a preliminary analysis of the transition problem from hovering to forward flight was made. A method of analysis for the ducted fan is reported and some preliminary design data have been obtained. The effect of hovering ceiling, cruise altitude and hovering duration on the optimum size was investigated.

The results of these investigations are presented in the following reports:

Report No.	Title
R-77	Propeller Aerodynamics of VTOL Aircraft
R-78	Unsteady Flight Problems of the Tilting Wing Propeller Aircraft
R-79	Transition Analysis of the Vertodyne
R-80	Ducted Fan Design Study of the Vertodyne
R-81	Preliminary Wing Weight Determination
R-82	STOL Capabilities of VTOL Aircraft

Report No.	Title
R-83	Performance and Weight Estimates for Six VTOL Aircraft
R-84	Effect of Performance Criteria on the Optimum Design of the Tilt-Wing Propeller and Vertodyne

C. Discussion

The six optimum VTOL concepts resulting from this study may be grouped into two categories; medium cruise speed aircraft (up to 350 mph) and potentially high speed cruise aircraft (400 mph and greater). The Tilt Wing Propeller, Tilting Ducted Propellers and Vectored Lift concepts fall into the first category while the Special Hovering Turbojet, Vertodyne and Vectodyne belong in the second category.

1. Tilt Wing Propeller

The Tilt Wing Propeller concept wherein the propellers are used for lift in hovering and forward flight thrust is perhaps most applicable in the field of medium speed VTOL aircraft. To meet the mission requirements, the gross weight is approximately 89,000 pounds and the aircraft is powered with six Allison 550-Bl turbo-props. A hovering capability at 6000 feet and 95°F is obtained at initial gross weight with water injection. The take-off gross weight of this aircraft varies appreciably with design performance requirements. These effects on gross weight have been a separate subject of investigation. The results are discussed in detail in Ref. 3 and summarized in Section IV of this report.

The design depicted here is the result of a very conservative approach. To assure engine-out safety, the propellers are interconnected. The engines are mounted on the fuselage so that they remain substantially horizontal and thus, the hot engine exhaust gases do not constitute an operational hazard when taking off or landing from unprepared fields. Once the assumptions of interconnected propellers and non-tilting engines are made, it is relatively easy to provide very effective pitch and yaw control in hovering and low speed flight through the use of submerged fans in the tail interconnected to the propellers. Roll control is obtained through differential thrust of the propeller. This conservative design approach results in an aircraft meeting all safety requirements for control in the event of engine failure at the expense of a more complicated drive system. Other arrangements were studied, which although mechanically simpler, unduly compromised safety requirements of the transport aircraft. For present-day and anticipated 1960 state of art, the proposed design arrangement is considered most practical.

The Tilt Wing Propeller employs four counter-rotating propellers, 21 foot in diameter with activity factor of approximately 180. The downwash velocity of about 200 mph (fully developed slipstream) is high and will undoubtedly cause difficulties from an operational viewpoint. The problems of high disc loading generators are associated with all VTOL aircraft visualized in this study, and is a subject requiring more detailed investigation.

2. Tilting Ducted Propeller

The Tilting Ducted Propeller is very competitive from a gross weight point of view with the Tilt Wing Propeller. Gross weight is approximately 93,000 pounds and it is also powered with six Allison 550-Bl's. Again it has been assumed that the ducted propellers are interconnected. Engines are mounted on the wing just outboard of the fuselage. Positive pitch and yaw control is obtained from submerged fans in the tail surfaces in hovering and low speed flight; roll control is obtained through differential propeller thrust. A hovering capability at 6000 ft. and 95°F is obtained at take-off gross weight with water injection.

The shrouds enable higher static thrust and consequently for this particular aircraft, optimum disc loading is considerably higher than for the Tilt Wing Propeller. In high-speed forward flight, however, the shroud contributes a substantial amount of drag which is obviously reflected in increased fuel consumption. Consequently, for the radius of action considered, gross weight of this aircraft is slightly higher than the Tilt Wing Propeller. Success of the Tilting Ducted Propeller concept obviously depends upon the shroud characteristics. Test work should be continued to determine the optimum shroud configuration for good static and high speed characteristics.

3. Vectored Lift

For true VTOL operation, the Vectored Lift concept will always be at somewhat of a performance disadvantage due to the losses in thrust that are accompanied with deflecting the slipstream through quite large angles. Consequently, for a given gross weight, the loss in thrust requires a greater power which is reflected mainly in increased power plant weight and its associated components. Gross weight of this concept is approximately 111,000 lbs. Four counter-rotating 25 foot diameter propellers are powered with eight Allison 550-Bl turboprops; two located in each propeller nacelle. Due to the angle of slipstream deflection that can be tolerated (approximately 70 degrees), the position of the aircraft for VTOL is rather awkward resulting in either a two-position or high nose gear. Preliminary analysis of these two approaches, indicated the high nose gear to be more desirable.

Pitching moments associated with hovering flight are high and have been alleviated somewhat in this design concept by lowering the propeller thrust line, and by use of a controllable forward located stabilizer which is immersed in the propeller slipstream. Additional pitch control is obtained by the tail submerged fan. From analytical studies made, the use of a forward located stabilizer for pitch control appears very promising. Experimental investigation is required to determine the feasibility of such an arrangement. Yaw control fans are located in the vertical fins. The propellers are all interconnected.

4. Special Hovering Turbojet

The concept of obtaining vertical take-off and landing with direct lift turbojets is appealing, since the compromises of the conventional airplane configuration are a minimum. However, it requires a new philosophy of engine installation. For the design concept visualized, 10 clusters of six modified J-85 turbojets would be required for vertical take-off at 6000 ft. and 95°F. Each cluster would be designed to operate as an individual engine with a single starting system, fuel system and associated accessories. Installation and operational problems of clustering engines for this purpose should be investigated more thoroughly. To achieve the high speed potential of this configuration special emphasis should be placed on the design of light-weight short-length turbojet engines. Short length is mandatory in order to bury the engines in the root wing section and be able to attain moderate airfoil thickness.

In addition to the hovering engines, three J-85 turbojets are installed in each wing for forward flight propulsion. Two J-85's are located in the tail for pitch and yaw control and may be used for forward propulsion. Roll control is obtained from bleed air of the wing mounted forward flight engines. The particular design submitted has marginal forward speed performance as a result of the minimum number of engines installed for forward thrust. Higher cruise speed could be attained simply by installing a forward flight power package capable of greater thrust with a corresponding increase in the normal gross weight.

Although the concept is interesting for higher cruise speeds there are several problems, other than power plant development, associated with this design for the assault transport mission. Perhaps the greatest detriment is the hot exhaust gases blasting downward in the take-off and landing flight conditions. Another drawback is the limited time available that can be spent in the VTOL regime of flight due to the high fuel consumption.

Gross weight of this aircraft (designed for cruising speed of 300 mph) is approximately 107,000 pounds.

5. Vertodyne

The Vertodyne concept becomes a very promising design for high speed VTOL assault transport applications. Ducted fans are located in the inboard sections of the wing to provide vertical thrust. The ducted fans are mechanically driven by a power turbine separated by means of ducting from the gas generator of the modified J-79 turbojets. Consequently, in hovering the engines are operated as turboprops and in forward flight as conventional turbojets.

Gross weight of this aircraft is approximately 114,000 pounds. It is powered with four modified J-79 turbojets, two mounted in each nacelle immediately outboard of each wing-submerged ducted fan. This aircraft has a maximum speed of 500 mph and a cruise speed of 400 mph at 10,000 ft. Since the wing area of this design must, of necessity, be large to accommodate the submerged ducted fans, cruising at still higher altitudes would be especially desirable.

Pitch and yaw control is obtained from shaft driven tail fans interconnected to the main lifting fans. Control of the aircraft in roll is obtained by differential thrust of the main lifting fans. Acceleration during transition can be achieved by tilting the aircraft forward to obtain a horizontal component of thrust from the ducted fans and deflecting the flaps in order to obtain the necessary lift coefficients at reduced angles of attack.

To realize the full potential of maximum and cruise speeds of this VTOL concept it is essential to develop and expand ducted fan designs of short overall depth in order to use moderate root airfoil thickness. Experimental and theoretical work aimed specifically at these requirements should be pursued.

6. Vectodyne

Due to the design requirements deemed essential for this particular transport mission, the basic configuration of the Aerodyne was somewhat compromised. The configuration presented herein consists of a central fuselage and two lift-thrust generators attached to the fuselage and has therefore been referred to as the Vectodyne. Consequently, the forward flight performance of the Vectodyne may be somewhat inferior as compared to the original concept.

The gross weight of this aircraft is approximately 122,000 lbs. and it is powered with nine Allison 550-B1 turboprops. Three engines are installed in each propeller afterbody and the three additional engines are located on the fuselage. The propellers are interconnected. Roll and pitch control is achieved through submerged tail fans; yaw control by flap deflection and differential main propeller thrust.

The aircraft is capable of hovering at 6000 ft. and 95°F at take-off gross weight with water injection. Cruising speed is 405 mph and maximum speed is 460 mph at 10,000 ft. One group of technical problems of the Vectodyne will result from the necessity of assuring an efficient performance of the thrust generator in various regimes of flight, while the other will be caused by safety requirements.

Problems belonging to the first group stem from the fact that in hovering the thrust generator exit velocity must be vertical, while in high speed flight it should become almost horizontal. This means that a system of turning vanes or other devices must be incorporated which would permit efficient direction of the flow from the thrust generators from vertical to almost horizontal. In this respect the problem becomes somewhat similar to directing the downwash of the vectored lift aircraft.

Special safety problems are resulting from the fact that both lift and control of this aircraft in all regimes of flight completely depend on functioning of the engines. Hence, even partial engine failure is more serious than in other concepts while complete engine failure will be catastrophic regardless of the regime of flight (except very close to the ground) in which it happens.

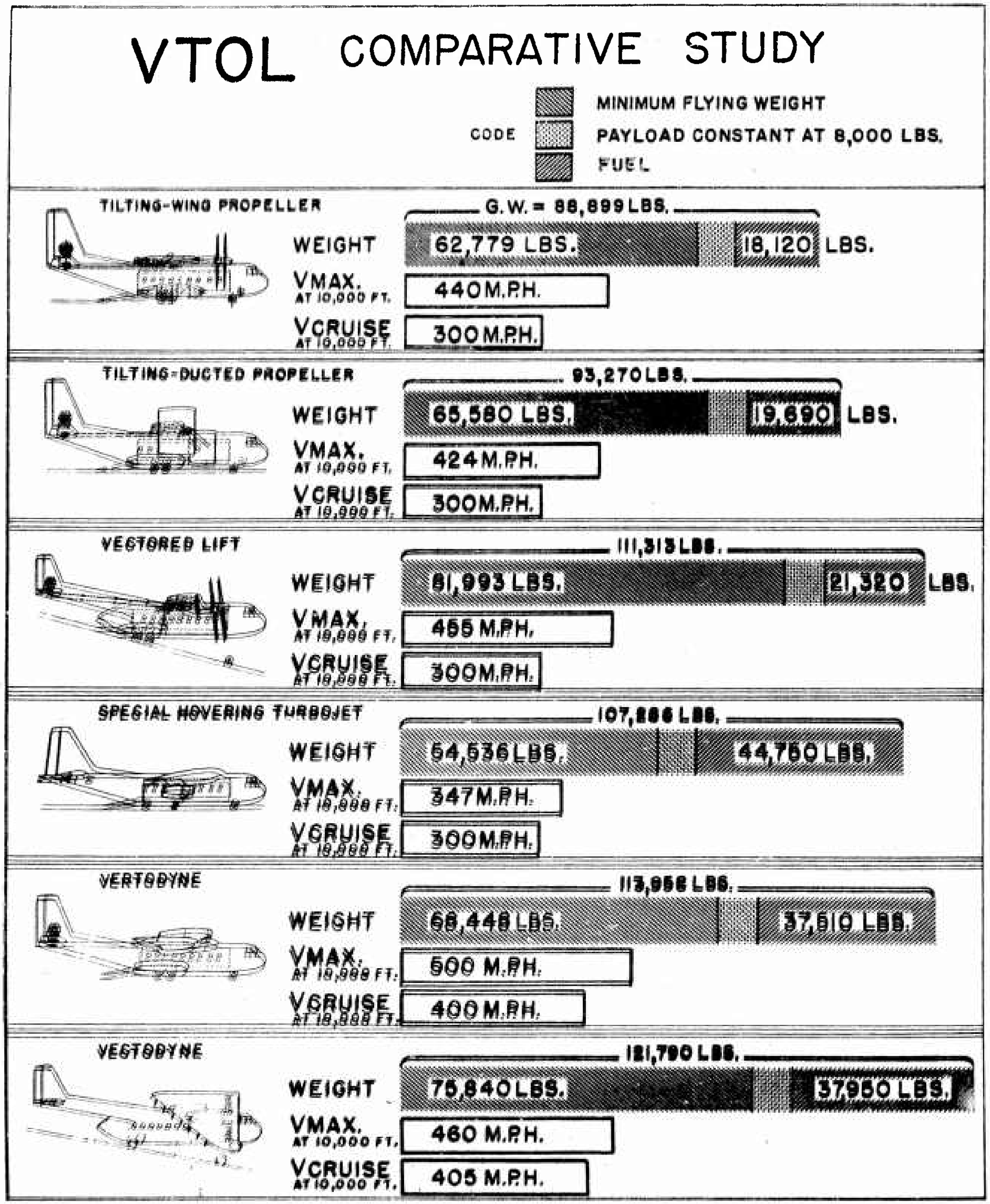
Since all studied aircraft were designed to carry the same payload over a given range at a given altitude, etc., basic differences between various concepts are illustrated by gross weight, fuel required to perform the mission, and cruising and maximum speeds. All these items are summarized on the following page.

D. Conclusions

From the results of the broad comparative study and the more detailed design studies, it is concluded that the following six configurations are suitable for fulfilling the mission requirements:

1. Tilt Wing Propeller
2. Tilting Ducted Propeller
3. Vectored Lift
4. Special Hovering Turbojet
5. Vertodyne
6. Vectodyne

The Tilt Wing Propeller and Tilting Ducted Propeller seem to be the optimum concepts for performing the specified mission at cruising speeds of 300 mph or slightly higher. The Vectored Lift concept shows a higher gross weight for the mission because of its inherently lower efficiency in the utilization of propeller thrust for lift generation. However, only actual flight experience may show whether this drawback will not be compensated by some design or operational advantages.


VTOL COMPARATIVE STUDY
CODE
MINIMUM FLYING WEIGHT
PAYLOAD CONSTANT AT 8,000 LBS.
FUEL
TILTING-WING PROPELLER
G.W. = 88,899 LBS.
WEIGHT
62,779 LBS.
18,120 LBS.
VMAX. AT 10,000 FT.
440 M.P.H.
VCRUISE AT 10,000 FT.
300 M.P.H.
TILTING-DUCTED PROPELLER
93,270 LBS.
WEIGHT
65,580 LBS.
19,690 LBS.
VMAX. AT 10,000 FT.
424 M.P.H.
VCRUISE AT 10,000 FT.
300 M.P.H.
VECTORED LIFT
111,313 LBS.
WEIGHT
81,993 LBS.
21,320 LBS.
VMAX. AT 10,000 FT.
455 M.P.H.
VCRUISE AT 10,000 FT.
300 M.P.H.
SPECIAL HOVERING TURBOJET
107,286 LBS.
WEIGHT
54,536 LBS.
44,750 LBS.
VMAX. AT 10,000 FT.
347 M.P.H.
VCRUISE AT 10,000 FT.
300 M.P.H.
VERTODYNE
113,956 LBS.
WEIGHT
68,446 LBS.
37,510 LBS.
VMAX. AT 10,000 FT.
500 M.P.H.
VCRUISE AT 10,000 FT.
400 M.P.H.
VECTODYNE
121,790 LBS.
WEIGHT
75,840 LBS.
37,950 LBS.
VMAX. AT 10,000 FT.
460 M.P.H.
VCRUISE AT 10,000 FT.
405 M.P.H.

For higher cruising speeds of say 400 mph and higher, the Special Hovering Turbojet and the Vertodyne become very attractive. However, the Vertodyne seems to indicate some advantage over the pure jet as it eliminates the problems of hot exhaust gases blasting against the ground and shows better characteristics in fuel consumption in hovering and near hovering flights. Both of these concepts can probably be made operationally available in the period of time similar to those of the Tilt Wing and Tilting Ducted Propeller.

Of all the six most promising concepts, the Vectodyne incorporates the largest amount of basic assemblies and parts whose weight trends and general performance cannot be established on the basis of statistical data. Because of the lack of this data, the design analysis of this type could not be as thorough as that of other aircraft, and more work is required to determine with certainty its competitive position with respect to the other most promising concepts. This absence of practical experience with many assemblies forming the Vectodyne concept may serve as an indication that this type of aircraft will probably require the longest time of development before it becomes operationally acceptable.

E. Recommendations

In order to acquire practical experience and to expand the basic technical knowledge of the VTOL aircraft, the following recommendations are made:

1. The flying test bed program should incorporate the design, construction and flight test of all six most promising VTOL concepts.

2. Operational problems resulting from high disc loading of VTOL thrust generators should be investigated with particular emphasis on such topics as:

   a. Operation from unprepared fields.
   b. Rescue capabilities and damage to nearby aircraft or equipment.
   c. Rise in ambient temperature when hovering in still air.
   d. Ignition of vegetation or injuries to personnel from high temperature exhausts.

3. Stability and control problems of VTOL aircraft at hovering and through transition should be investigated. Safety aspects of interconnected power plant should be compared with other possible solutions. Artificial stabilization through attitude and rate gyroscopes should be analyzed.

4. A design study should be initiated in order to obtain a design handbook for VTOL and STOL propellers. This study should cover aerodynamics, design and weight aspects.

5. Additional aerodynamic data applicable to ducted fan concepts should be obtained. In particular, cascade studies should be extended to cover the whole possible range in inlet angles.

6. Future power plant development programs should include the following:

   a. Means of improving turboprop and turbojet performance at elevated altitudes and ambient temperatures.

   b. The operational aspects of clustering small light weight turbojets should be investigated.

   c. The advantages of "free-turbine" turboprops should be evaluated against the variable transmission concept.

   d. Methods of employing the same hot gas generator for driving a power turbine in hovering and transition, as well as supplying direct jet propulsion for high speed flight (Vertodyne principle) should be studied in greater detail including actual test.

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I. INTRODUCTION

A. Objectives

Due to recent advances in the technology of turbo-engines, the development of aircraft capable of vertical take-offs and landings as well as of much higher flying speeds than contemporary helicopters has received great impetus. Actual flights of such aircraft as the Convair and Lockheed "pogo stick" fighters, Bell's direct-lift turbojet flying test bed and the flying "bedstead" of Rolls-Royce has demonstrated the feasibility of vertical take-off and landing of aircraft other than the conventional helicopter.

Vertical or short take-off and landing (VTOL or STOL) capabilities combined with relatively high cruising speeds is especially attractive for the transport aircraft. With either VTOL or STOL capabilities, a higher degree of mobility of Army units and independence of prepared fields is assured. In the concept of atomic warfare, these operational requirements are mandatory.

Obviously, however, the application of VTOL or STOL principles can not compromise the basic requirements of the transport aircraft. Therefore, some characteristics which could be tolerated, for instance, in fighters, become entirely unacceptable for transports.

Efficient loading and unloading operations dictate that the transport fuselage remain basically horizontal while the aircraft is on the ground. Also, it should remain horizontal in all flight regimes, from hovering or low speed flight to maximum speed.

Furthermore, loading requirements of such equipment as jeeps, weapons carriers, bulk equipment, etc., require the need of a rear aperature door with integral loading ramp. Controlability, stability and general safety requirements can not be compromised in any manner for this type of aircraft where large number of troops may be transported. These requirements must be met and obviously are more severe than either for fighters or small observation aircraft.

Safety requirements definitely indicate the necessity of complete controlability of the aircraft in the case of engine failure. It is also obvious that it is absolutely necessary to assure a controlled landing of the aircraft in the case of complete engine failure. It is evident that the loading and safety requirements must have a profound influence on the whole design philosophy and must be reflected in the ultimate configuration of this type of aircraft.

Recognizing the fact that the incorporation of the VTOL or STOL principles into transport aircraft will create special technical problems, the Office of Naval Research and the Army Transportation Corps jointly awarded several design studies of particular types of VTOL and STOL aircraft. In addition, two contracts were given for general studies; one for STOL and one for VTOL aircraft. This contractor was awarded a general study of the VTOL transport aircraft which may be suitable for performing the following mission:

1.	Payload	8000 lb. out - 4000 lb. back
2.	Take-off	Vertical
3.	Cabin Size	8' x 9' x *
4.	Cargo	35 Infantry troops or equivalent vehicles
5.	T.O. Conditions	Pressure altitude 6000 ft. at 95°F
6.	Runway Surface	Friction coefficient μ = .2; UCI = 15**
7.	Cruise Speed	300 MPH
8.	Flight Profile	20% of radius adjacent to target at S.L.
9.	Landing	Vertical
10.	Radius of Action	425 Statute miles

* As required to accommodate 35 troops.
** Applicable to the case of running take-off at overload gross weight.

Furthermore, it was specified the aircraft must remain controllable with one engine inoperative and be able to make a "controlled crash" landing.

B. General Method of Solution

In order to select the aircraft most suitable for this mission, the study started with a review of all concepts of vertical take-off and landing which had the potentiality of fulfilling the transport mission. Since the helicopter is, at present, the only operational VTOL aircraft, the study obviously started with reviewing various concepts based on the rotary wing concept. Special emphasis was put on the problem of increasing the cruising and maximum speed of these aircraft beyond that of present day helicopters. In addition to the rotary wing concepts, it was possible to visualize various aircraft using special vertical thrust generators for hovering and near hovering flight and depending on fixed wings for high speed flights.

A separate category is formed by the Aerodyne where vertical thrust in hovering and near hovering conditions, as well as in high speed forward flight is generated by the same lifting and propelling thrust generator. In this concept, the wing is completely eliminated and replaced by the combined lift and propelling thrust generator.

In order to evaluate all the various concepts on a common basis, and properly judge their suitability for the transport mission, a broad comparative study of all VTOL concepts was undertaken. The main difficulty in the analysis was the lack of accurate design or statistical data, except for the helicopters, which could be used directly in this parametric study. In order to obtain sufficient data, a thorough search of literature was undertaken, information regarding weight trends of components similar to those required for VTOL was collected, as well as numerous layouts of the whole aircraft and their components were made.

Preliminary results of the literature survey were reported in Reference (13), while weight studies were reported in Reference (1), and special design studies were reported in References (6, 7, 10, 11 and 12) and are also summarized in Section IV of this report.

Since the original intent of the subject contract was to reflect 1962 state of art, it was necessary to extrapolate the past and present trends of engine design data to this period of time.

In order to establish power plant trends, numerous discussions were held with representatives of engine manufacturers. Future trends were anticipated on the basis of a graphical presentation of the past and present engine characteristics. The results of the original study were reported in Reference (1) and for convenience are summarized in Section II of this report.

A similar approach was also applied to the weight trends of propellers and other components. After establishing the necessary weight characteristics trends, it became possible to conduct the parametric study and to determine the configurations most promising for the defined transport mission.

In any parametric study, a proper selection of actual parameters is of great importance. Recognizing this fact, pertinent parameters reflecting either design or operational aspects were varied to assure an optimum configuration. Parameters selected for the rotary wing concepts and those for the fixed wing and aerodyne configurations are listed in Section II of this report.

Finally, before the comparative study could be started, the time in hovering had to be defined. In order to assure operationally acceptable VTOL aircraft it was deemed necessary to assume an adequate time in hovering to permit a close survey of the landing site and to provide sufficient margin in the event this area was not suitable for landing for conversion into forward flight and finally to effect a vertical landing. On the basis of discussions with operational personnel, a 5 minute hovering duration allowance was established for this maneuver. In addition, a two minute warm-up was assumed. Consequently, a total time of seven minutes was used in calculating fuel requirements in hovering. Having made these assumptions and having established structural weight and power plant trends, it was possible to conduct the parametric comparative study. The results of this study were reported in Reference (1), and summarized briefly in Section II of this report. The most promising concepts were selected for more detailed design study and design optimization. Finally, detailed performance charts were calculated. For these aircraft, characteristics charts were prepared and are reported in Reference (2).

C. Detailed Studies

Upon reviewing the results of these design studies, it was apparent that the Tilt Wing Propeller aircraft was the optimum VTOL concept for cruising speeds of 300 to 350 mph while the Vertodyne appeared most suitable at higher cruising speeds. These two configurations, consequently, were selected for further analysis. Due to the limited scope of the subject contract, only some of the problems peculiar to each configuration were investigated.

For the Tilt Wing Propeller aircraft, a study was made of the propeller aerodynamics in order to determine the compromises that may be involved for achieving required thrust for hovering and forward flight. Transition from hovering to forward flight and the reverse procedure and engine-out descent analyses were also made. The potential of this configuration for STO (short take-off) operation was analyzed. To assure proper wing weights, a stress analysis of a tilting wing was undertaken. Finally, an investigation was made to determine the effect of hovering ceiling, cruise altitude and hovering duration on the optimum size of the aircraft.

For the Vertodyne aircraft, a preliminary analysis of the transition problem from hovering to forward flight was made. A method of analysis for the ducted fan is reported and some preliminary design data have been obtained. The effect of hovering ceiling, cruise altitude and hovering duration on the optimum size was investigated.

The results of these investigations are presented in References (2, 3, 6, 7, 9, 10, 11 and 12), and summarized in Section IV of this report.

II. PARAMETRIC STUDY

In May 1955, Vertol Aircraft Corporation was awarded Contract Nonr 1681(00) from the Office of Naval Research, Department of the Navy, to undertake a broad research comparative study of vertical take-off and landing subsonic transport aircraft.

A. Relative Competitive Position of VTOL Configurations

In the initial phase of the study, (Reference 1), all possible design concepts for VTOL transports were considered. A parametric study was undertaken to determine the relative competitive positon of the many configurations conceived for VTOL transport applications.

To accomplish this task, technical data for various VTOL design concepts, with particular emphasis on trends of component weights and powerplant data, were compiled and consolidated into a useable form. Using the trend data, the minimum take-off gross weight required to perform the specified mission was evaluated and presented as a function of cruise speed. In keeping with the original intent of the study, the trend data was extrapolated to reflect 1962 state of art.

The VTOL configurations studied were divided into two distinct categories, rotary wing and fixed wing aircraft. Several combinations of powerplants were assumed for each configuration. The various configurations studied in this study are tabulated below:

1. Rotary - Wing Concepts

Configurations	Power Plant: Hover	Power Plant: Cruise
a. Conventional Tandem Rotor Helicopter	Turboprop	Turboprop
b. Tandem Rotor Helicopter equipped with BLC Rotors	Turboprop	Turboprop
c. Compound Helicopter	Turboprop	Turboprop
	Rocket Turbine	Turboprop
	Tip Rocket	Turboprop
d. Retractoplane	Turboprop	Turboprop
	Rocket Turbine	Turboprop
	Tip Rocket	Turboprop
	Rocket Turbine	Turbojet
	Tip Rocket	Turbojet

2. Fixed Wing Concepts

Configurations	Power Plant Hover	Power Plant Cruise
a. Tilt Wing	Turbojet Turboprop By-Pass Turbojet	Turbojet Turboprop By-Pass Turbojet
b. Deflected Thrust	Turbojet By-Pass Turbojet	Turbojet By-Pass Turbojet
c. Vectored Lift	Turboprop	Turboprop
d. Breguet-Kappus	Split-turboprop	Split-turboprop
e. Special Hovering Turbojet	Turbojet (1)	Turbojet
f. Tilting Ducted Propeller	Turboprop	Turboprop
g. Aerodyne	Turboprop (2)	Turboprop (2)

Notes: (1) Special high thrust - light weight hovering engines arranged in clusters.
(2) Shrouded propeller.

To determine the optimum combination of aerodynamic and design parameters for establishing minimum take-off gross weight as a function of cruise speed, the following items were varied for each design concept:

DESIGN CONCEPT	ITEMS VARIED
3. Rotary Wing Concepts	
a. Conventional Tandem Rotor Helicopter	$\omega, V_t, \bar{C}_L$
b. Tandem Rotor Helicopter equipped with BLC Rotors	$\omega, V_t\ C_{L_{MAX}}$
c. Compound Helicopter	ω, V_t, C_{L_W}, AR
d. Retractoplane	ω, V_t, C_{L_W}, AR
4. Fixed-Wing Concepts	
a. Tilt Wing Propeller	ω, V_t, C_{L_W}
b. Tilt Wing Turbojet	C_{L_W}, AR
c. Tilt Wing By-Pass Turbojet	C_{L_W}, AR
d. Tilting Ducted Propeller	ω, C_{L_W}, AR
e. Special Hovering Turbojet	C_{L_W}, AR

DESIGN CONCEPT	ITEMS VARIED
f. Deflected Turbojet Thrust	C_{LW}, AR
g. Deflected By-Pass Turbojet	C_{LW}, AR
h. Vectored Lift	W, V_t
i. Breguet-Kappus	W, AR
j. Aerodyne	W

The results of this study is presented graphically (Figure 1) in terms of take-off gross weight required to meet the mission specifications as a function of cruise speed. Several deviations were made in order to evaluate the numerous VTOL design concepts as quickly as possible:

a. Payload - 8,000 pounds outbound and inbound
b. Cruise at sea level
c. Cruise at 80% of rated military power.

These deviations were made to simplify the calculations and do not effect trends but merely result in conservative (heavy) estimates for take-off gross weight. It was further assumed that a total hovering duration of five minutes at military power would be required to effectively perform the basic mission.

It should be realized that this initial study was prepared to determine trends and the approximate competitive position of the various VTOL design concepts. The trends were established through a parametric analysis taking into consideration both the weight and aerodynamic aspects of the problem.

Of the many VTOL transport concepts investigated, the following six designs appeared to be the most suitable for fulfilling the mission requirements at cruising speeds of 300 mph or greater:

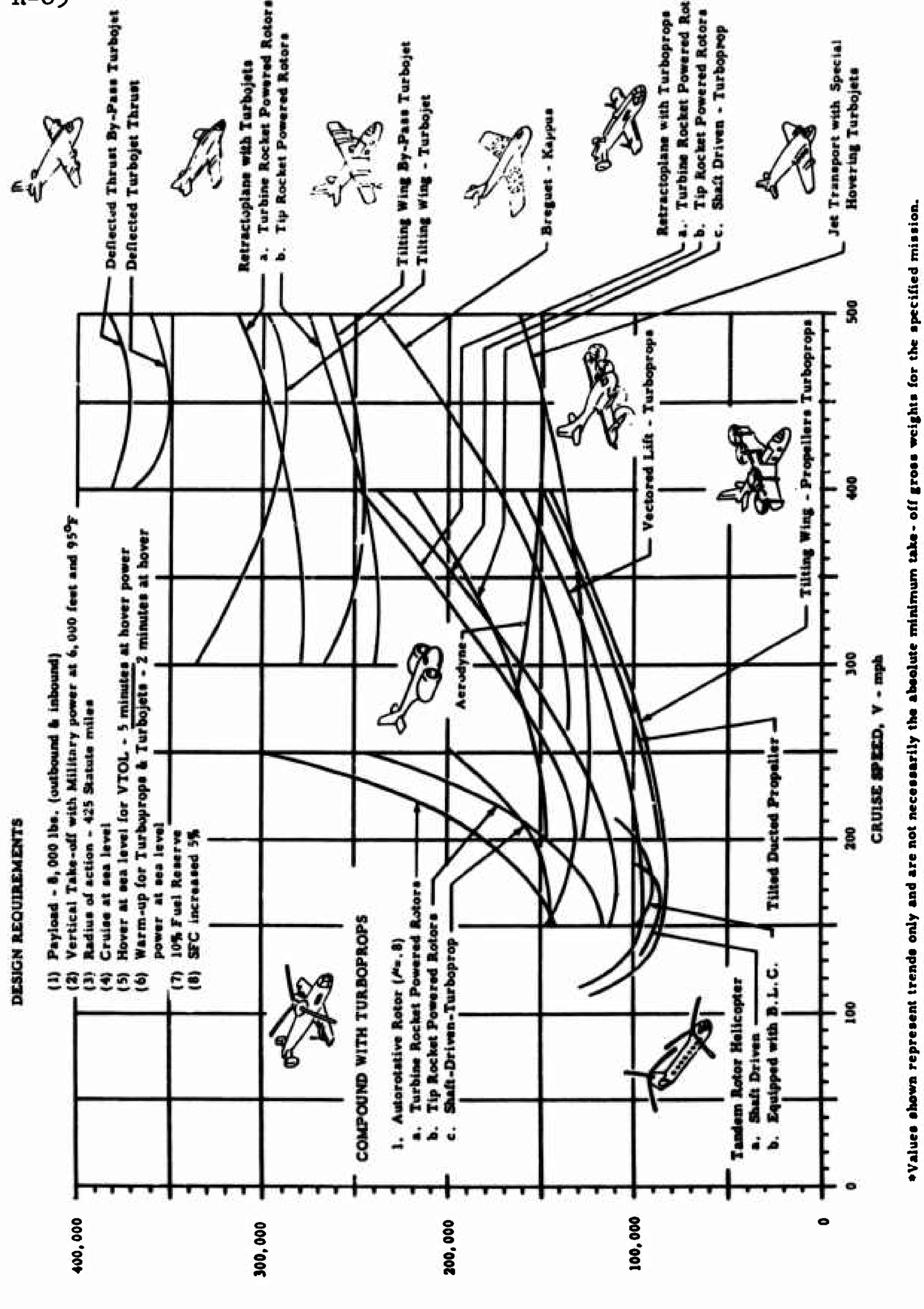
1. Tilt Wing Propeller
2. Tilting Ducted Propeller
3. Vectored Lift
4. Special Hovering Turbojet
5. Vertodyne (Breguet-Kappus)
6. Aerodyne

These six configurations for the VTOL transport application were subjected to a more detailed study and evaluated for the specified mission using power plants that will be available in the period 1956-1960. These studies are summarized in Section III and reported in greater detail in Reference (2).

FIG. 1

COMPARATIVE STUDY OF VARIOUS TYPES OF VTOL AIRCRAFT

TAKE-OFF GROSS WEIGHT * VS CRUISE SPEED



*Values shown represent trends only and are not necessarily the absolute minimum take-off gross weights for the specified mission.

B. Weight Trends

Since the purpose of this study was to indicate the competitive position of the various VTOL concepts, the weight analysis was geared to the prediction of accurate trends rather than detailed absolute numbers.

Development of weight expressions for VTOL aircraft were based on the premise that fixed wing and rotary wing weight trends, with adjustments made to reflect special features and problems, could be combined to predict VTOL weight trends. The design parameters for correlating weight trends were selected principally for this investigation.

Detailed methods and data for correlating basic component weights are reported in Reference (1). Summary charts showing the application of these trends are presented in Table I and II of this report. It should be noted that the trend data for the Tilt Wing Propeller and Vertodyne has been adjusted and reported in more recent studies (Reference (3)) to better reflect the weight for the specific design configuration. These changes consists mainly of adjustment to the drive system weight trends for fuselage mounted engines, of slight increases in weight of the alighting gear and tail groups, and reduction of the wing weight constant for the Tilt Wing Propeller aircraft.

C. Power Plant Trends

Since the performance and therefore the competitive position of VTOL aircraft is dependent to a large extent on low specific weight and fuel consumption power plants, the need to predict future power plant design trends accurately was exceedingly important. Performance and weight data for various aircraft development and study engines was obtained from cognizant engine manufacturers. This data is summarized in Table III. The specific fuel consumption and specific weight of representative shaft turbine, turbojet and by-pass turbojet engines were plotted against the date of availability to allow the construction of curves representing the trend of technological improvement from which predicted 1962 values were obtained. Table IV presents the predicted 1962 state of art performance and weight data for various engine types considered in this study. The reciprocating engine was not considered as a candidate power plant for this study due to its bulk installed weight and development stagnation. Complete power plant trend data is reported in Reference (1).

TABLE I - SUMMARY VTOL WEIGHT TRENDS -- ROTARY WING CONCEPTS

Retractoplane Single Rotor with Propellers			Retractoplane Single Rotor with Turbojets		Correlation Factor K
Shaft Driven Rotor: Gas Turbine	Shaft Driven Rotor: Turbine Rocket	Tip Rocket Driven Rotor	Shaft Driven Rotor Turbine Rocket	Tip Rocket Driven Rotor	
←		$(1.2)(226K^{0.63})$		→	$\frac{WR\sigma^2}{V_T \times 10^2}$
←		$(1.2)(92.4K^{0.53})$		→	$WRHP \times 10^{-7}$
←		$1.06\left[41.57 C_1 \omega_W^{.025} S + \frac{0.6(LF) b^3 \omega_W (TF)}{f}\right]$		→	
.03W	.03W	.019W	.03W	.019W	
← $1.33\left[496K^{0.34}\right]$ →		$(1.21)(496K^{0.34})$	$(1.33)(496K^{0.34})$	$(1.21)(496K^{0.34})$	$W^2 S_F \times 10^{-10}$
←		.04W			→
.51 #/HP	.09 #/HP + 360	.145 #/#THRUST	.09 #/HP + 360	.145 #/#THRUST	
	.51 #/HP	.51 #/HP	.277 #/#THRUST	.277 #/#THRUST	
←		.2 #/HP		→	
$270K^{0.674}$	$270K^{0.674}$	ROTOR SHAFT = .01W	$270K^{0.674}$	ROTOR SHAFT = .01W	$\frac{HP}{\Omega}$
$130K^{0.5} \times N$	—	—	—	—	$\frac{HP_X}{\Omega_X}$
$6.5K^{0.5} \times L$	—	—	—	—	$\frac{HP_S}{\Omega_S}$
←		2380 + .045W		→	
9500	9500	9050	9500	9050	
6.65 #/GAL	8.5 #/HP/HOUR	15 #/#THRUST/HR	8.5 #/HP/HOUR	15 #/#THRUST/HR	
	6.65 #/GAL	6.65 #/GAL	6.65 #/GAL	6.65 #/GAL	

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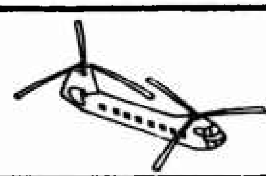
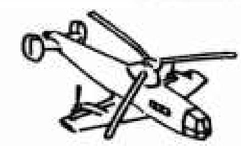
TABLE I - SUMMARY VTOL WEIGHT TRENDS - ROTARY WING CONCEPTS





Item	Tandem Helicopter Shaft Driven Rotors		Compound Helicopter Single Rotor with Propellers		
			Shaft Driven Rotor		Tip Rocket Driven Rotor
	Conventional Rotor	BLC Rotor	Gas Turbine	Turbine Rocket	
Rotor Group/Rotor Blades	$226K^{0.63}$	$(1.1)(226K^{0.63})$	←	$226K^{0.63}$	→
Hub & Hinge	$92.4K^{0.53}$	$(1.1)(92.4K^{0.53})$	←	$92.4K^{0.53}$	→
Wing Group	—	—	← $1.06\left[41.57C_1 \omega_W^{0.25} S + \frac{0.6(LF)b^3\omega_W(TF)}{f}\right]$ →		
Tail Group	.01W	.01W	.029W	.029W	.019W
Body Group	← $1.7[496K^{0.34}]$ →		← $1.26[496K^{0.34}]$		1.15X →
Alighting Gear*	←		.04W		→
Propulsion Group Rotor	.42 #/HP	.42 #/HP	.51 #/HP	.09 #/HP + 360	.145 #/THRUST
Props or Jets	—	—		.51 #/HP	.51 #/HP
Propellers	—	—	←	.2 #/HP	→
Drive System Rotor Drive	$610(.6K)^{0.674}$	$610(.6K)^{0.674}$	$305K^{0.674}$	$305K^{0.674}$	ROTOR SHAFT = .01W
Prop. Sync. XMSN	—	—	$130K^{.5}N$	—	—
Prop. Sync. Shafting	—	—	$6.3K^{.5}L$	—	—
Fixed Equipment**	2380 + .03W	2380 + .03W	←	2380 + 0.35W	→
Fixed Useful Load Incl. Eng. Lub. Sys.**	←	9500		→	9050
Fuel & Fuel System Rotor	6.7 #/GAL	6.7 #/GAL	6.65 #/GAL	8.5 #/HP/HOUR	15 #/#THRUST/HR
Props or Jets				6.65 #/GAL	6.65 #/GAL

* Retractable - Helicopter Design Criteria

** These values apply only for the gross weight range and mission of this study.

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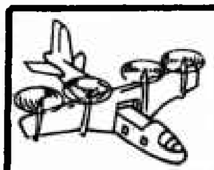
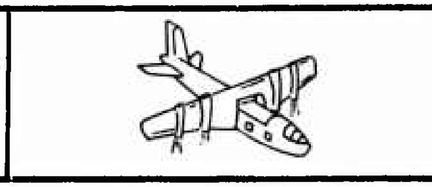
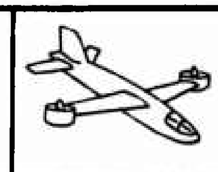
TABLE II - SUMMARY VTOL WEIGHT TRENDS-FIXED WING CONCEPTS

					
	Tilting Wing			Tilting Ducted Propeller	Special Hovering Turbojet
Item	Turboprop[1]	By-Pass Turbojet	Turbojet	Turboprop	
Rotor Group/Rotor	$748K^{0.31}$	INCLUDED IN ENGINE WT.	—	—	—
Wing Group	$1.2x$	$1.2x$	$1.2x$ $1.06\left[41.57C_1 w_w^{.25} S + \frac{0.6(LF)b^3 w_w(TF)}{F}\right]$	$1.1x$	$1.0x$
Tail Group	.03W				.03W
Body Group			$496K^{0.34}$		
Alighting Gear*	.045W	.04W	.04W	.04W	.04W
Propulsion Group Fwd. Flight	.51 #/HP	.306 #/#THRUST	.277 #/#THRUST	.53 #/HP	.277 #/#THRUST
Vert. Flight					.12 #/#THRUST
Propeller/Prop.	—	—	—	$2.0S_5 + 1250K^{0.27}$	—
Drive System Prop. Sync. XMSN	$130K^{.5}N$	—	—	$130K^{.5}N$	—
Prop. Sync. Shafting	$6.3K^{.5}L$	—	—	$6.3K^{.5}L$	—
Prop. Extension Shaft	7.2KL	—	—	7.2KL	—
Fixed Equipment**	2380+.026W	2380+.015W	2380+.015W	2380+.025W	2380+.02W
Fixed Useful Load Incl. Eng. Lub. Sys.**	9300	9150	9150	9300	9150
Fuel & Fuel System Rotor		6.7 #/GAL		6.65 #/GAL	6.65 #/GAL

* Retractable - Helicopter Design Criteria

** These values apply only for the gross weight range and mission of this study.

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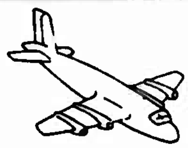
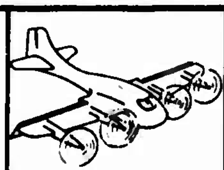
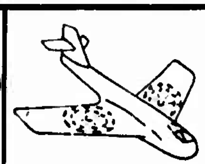
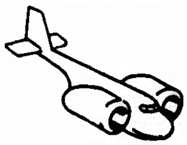
TABLE II - SUMMARY VTOL WEIGHT TRENDS-FIXED WING CONCEPTS

Deflected Thrust		Vectored Lift	Brequet-Kappus	Aerodyne	Correlation Factor K
					
Turbojet	By-Pass Turbojet	Turboprop	Split Turboprop[1]	Turboprop	
——	INCLUDED IN ENGINE WT.	$748K^{0.31}$	——	——	$\left(\frac{HP \times D^3 \times \sigma^{.5}}{\Omega \times 10^4}\right)$
1.0 × ←	1.0 × ←——	1.2 × 1.06 [41.57 $C_1 w_w^{.25} S$ +	1.30 × $\frac{0.6 (LF) b^3 w_w (TF)}{t}$] →	$2.5 S_S \ell$	
.03W ←	———	———	——— →	.03W	
←———	———	$496 K^{0.34}$	———	——— →	$W^2 S_F \times 10^{-10}$
.04W	.04W	.05W	.04W	.04W	
.29 #/# THRUST	.345 #/# THRUST	.51 #/HP	.56 #/HP	.53 #/HP	
——	——	——	$1250K^{0.27}$	$1250K^{0.27}$	$\frac{HP \times D^3 \times \sigma^{.5}}{\Omega \times 10^4}$
——	——	←——	$130K^{.5}N$	——→	$\frac{HP_x}{\Omega_x}$
——	——	←——	$6.3K^{.5}L$	——→	$\frac{HP_S}{\Omega_S}$
——	——	←——	7.2 K L	——→	$\frac{HP_P}{\Omega_P}$
2380 + .015W	2380 + .015W	2380 + .015W	2380 + .025W	2380 + .025W	
9150	9150	9300	9150	9300	
6.65 #/GAL	6.65 #/GAL	←——	6.7 #/GAL	——→	

(1) See Ref. 3 for the adjusted weight trends used for the detail study of these concepts.

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TABLE III - ENGINE SUMMARY LIST

Manufacturer	Type	Model No.	Specification or Report Number	Take-off SHP	Military SHP	Engine Weight Pounds	Military SFC	Date of Availability		
Allison	Shaft	XT38-A-3	374-A	1800	1800	1240	.800	1954		
	Turbine	T40-A-6	300-D----	5302	5302	2064	.683	Jan 1954	*	
		YT56-A-1	276-F	3017	3017	1575	.616	Jan 1955	*	
		YT56-A-5	391	3490	3490	1120	.580	Oct 1956	*	a
		T56-A-1	339-B	3460	3460	1645	.585	Jan 1955	*	
		501-D8	377-B	3755	3755	1660	.561	Mar 1957	*	a
		500-C14	382	7510	7510	3150	.560	36 MFGA	*	
		500-C15	383	6920	6920	3380	.585	48 MFGA		
Allison		550-B1	394-A	5200	5200	2150	.508	Sept1959		
Proposed		Twin Spool	Proposed	5930	5930	2150	.524	Sept1959	*	
General Electric		XT58-GF-2	SE-1	1024	1024	325	.660	Summer 1956	*	a
Pratt & Whitney		T-34	3529	5500	5300	2590	.695	1953		
Pratt & Whitney		T-57		13340	13340	6600	.606	Dec 1958	*	
Westinghouse		RB109	TSD449	4020	3280	1850	.515	1958	*	
Lycoming		XT55-L-1	127.1	1595	1458	600	.707	Dec 1957	*	a
Curtiss-Wright	Shaft Turbine	YT49-W-1	875-E	8500	8500	4466	.803	Current		
				(# Thrust)	(#Thrust)					
General Electric	Ducted	X84	R54AGT105	32900	16900	5100	.619	unknown		
	Fan	X84A	R55AGT22	17400	17400	4300	.593	Jul 1959	*	
Curtiss-Wright		WTF4	AC-215A	32000	18000	7000	.640	1960		
		WTF5	AC-216A	19200	19200	5500	.605	1960	*	
Westinghouse		R.Co.7	TSD 568	13000	12000	3731	.722	1957	*	
	Ducted	PD42-1		16500	16500	3550	.690	1961	*	
	Fan	PD42-2	WAGT F42.2.1	27200	16000	5425	.715	1962		
Allison	Turbojet	J71-A-2	361-C	14000	9850	4889	.955	Jul 1955		
		J71-A-9	356-B	9570	9570	4090	.880	May 1954		
		J71-A-11	381-B	9700	9700	4090	.880	Apr 1955		b
		600-B44	403	13600	9500	4890	.900	Apr 1957		b
		700-PD8	0000-HPD-X12	18000	12000	3280	.825	unknown	*	
		700-PD9	0000-HPD-X12	37500	25000	7320	.825	unknown	*	
General Electric		J47-GE-15	E-582	6000	5200	2515	1.130	1949	*	
		J47-GE-23	E-591-B	5910	5620	2512	1.028	1951	*	
		J73-GE-3			8920	3880	.917	1952	*	
		J79-3	R53AGT78	14350	9300	3255	.860	Sept1956		
		J79-216	R55AFT400	15600	10000	3255	.839	Jul 1957	*	b
		J79-207	R54AGT571	18000	12000	3500	.834	Jul 1959	*	
		MX2273	R55SE5	2450	2450	231.4	.910	Spring 1957		
		SJ-110-C1	R55SE19	3520	2470	327	.99	Nov 1957		
General Electric		SJ-110-C3	R55SE19	3621	2470	333.1	.99	Nov 1957		
Pratt & Whitney		J57-1	1680	12500	11200	3790	.775	Fall 1956		
		J57-2	1696	13750	11200	3865	.775	Summer 1957		
		J57-20	1661	17200	10950	4720	.810	Apr 1957		
		J75-1	1660	15800	15800	5300	.770	Mar 1957		b
		J75-24	2604	23500	15500	6100	.800	Mar 1957	*	b
		J75-21	5900	25000	16500		.830	Aug 1958		
Pratt & Whitney		J52 A/B	Inst. Hbk.	11000	7250	2750	.820	1960	*	
Pratt & Whitney		J52		7800	7800	2000	.820	1960	*	
Curtiss-Wright		J65-W-4	N890-A	7700	7700	2750	.915	1955		
		J65-W-6	N898	11000	7600	3485	.930	Jul 1955	*	b
		J65-W-7	892-E					1955	*	b
Westinghouse		PD33-1	WAGT228B-C	6075	6075	1425	.860	1957	*	
		PD33-2	WAGT128B-B	10000	6800	1960	.950	1958	*	
Fairchild		FT108A	298	2450	2450	325	.940	unknown		
		FT108B	301	3550	2360	415	.980	unknown		

TABLE IV

POWER PLANT TREND DATA

	Shaft Turbine Geared approx. 1000 RPM	Shaft Turbine Direct approx. 10500 RPM	Turbojet over 10000# Thrust after-burner	Turbojet over 10000# Thrust non-augmented	2450# Thrust non-augmented	By-Pass Turbo-Jet	Rocket on Rotor	Propellant Shaft Turbine
Specific Weight (#/SHP Mil.)	.327	.238						.09 + 360# per engine
Specific Weight (#/ESHP Mil.)	.309	.226						
Specific Weight (#/# Thrust TO)			.174	.208	.10			
Specific Weight (#/# Thrust Mil.)			.264	.208	.10	.230	.145	
Specific Fuel Con. (#/SHP Mil/Hr.)	.500	.500						8.5
Specific Fuel Con. (#/ESHP Mil/Hr.)	.474	.474						
Specific Fuel Con. (#/# Thrust TO/Hr.)			1.50	.798	.91			
Specific Fuel Con. (#/# Thrust Mil/Hr.)			.82	.798	.91	.590	15.0	
% Power Available at 6000' at 95°F	67%	67%	72%	72%	72%	70%	103%	103%

Another method presenting power plant characteristics is by means of Pearson's merit factor, as suggested in Reference (4). For turboprops this factor is defined as:

$$\text{Pearson's Merit Factor} = \frac{1}{SFC}\sqrt{\frac{SHP}{W_{ENG}}}$$

and plotted as a function of data of availability in Figure 2.

For turbojets, Pearson's merit factor has been modified to incorporate engine static thrust instead of shaft horsepower (SHP) and is shown in Figure 3.

Data for these curves were obtained from Table II for those engines denoted with an asterisk *. It is interesting to note the trends with availabilities and the expected technological gains by the year 1962. The resulting data agrees reasonably well with the trends of Reference (1).

FIGURE 2

PEARSON'S MERIT FACTOR FOR TURBOPROP ENGINES

SYMBOLS	MANUFACTURER	MODEL NO.
○	Allison	T40-A-6
▽	Allison	YT56-A-1
□	Allison	T56-A-1
◇	General Electric	XT58-GE-2
△	Allison	YT56-A-5
0	Allison	501-D8
⊂⊃	Lycoming	XT55-L-1
◁	Westinghouse	RB109
▷	Pratt & Whitney	TSD449
×	Allison (Proposed)	Twin Spool

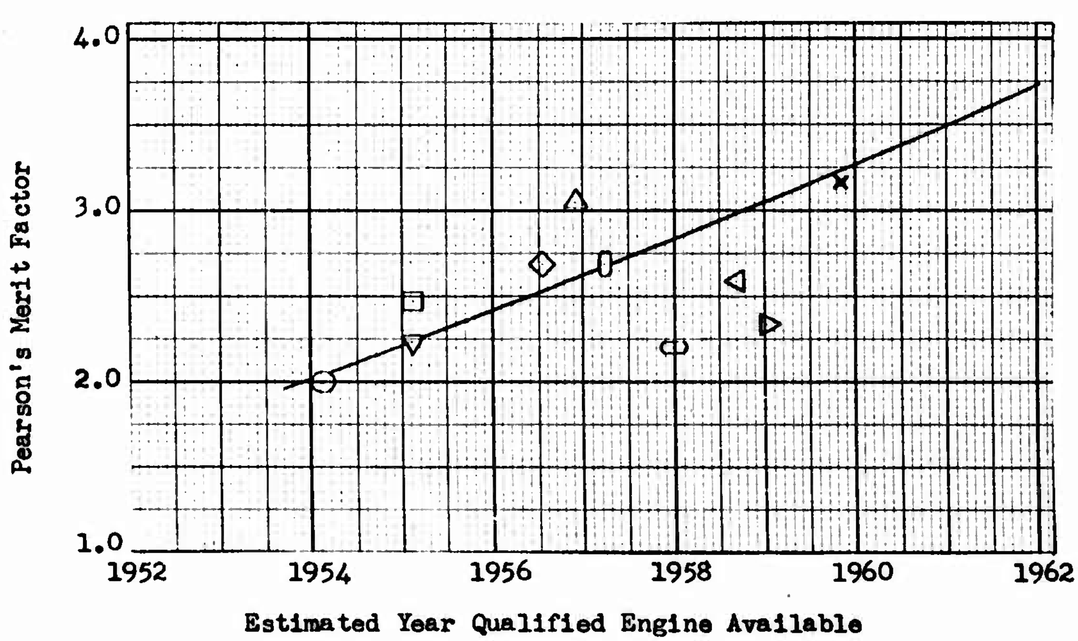

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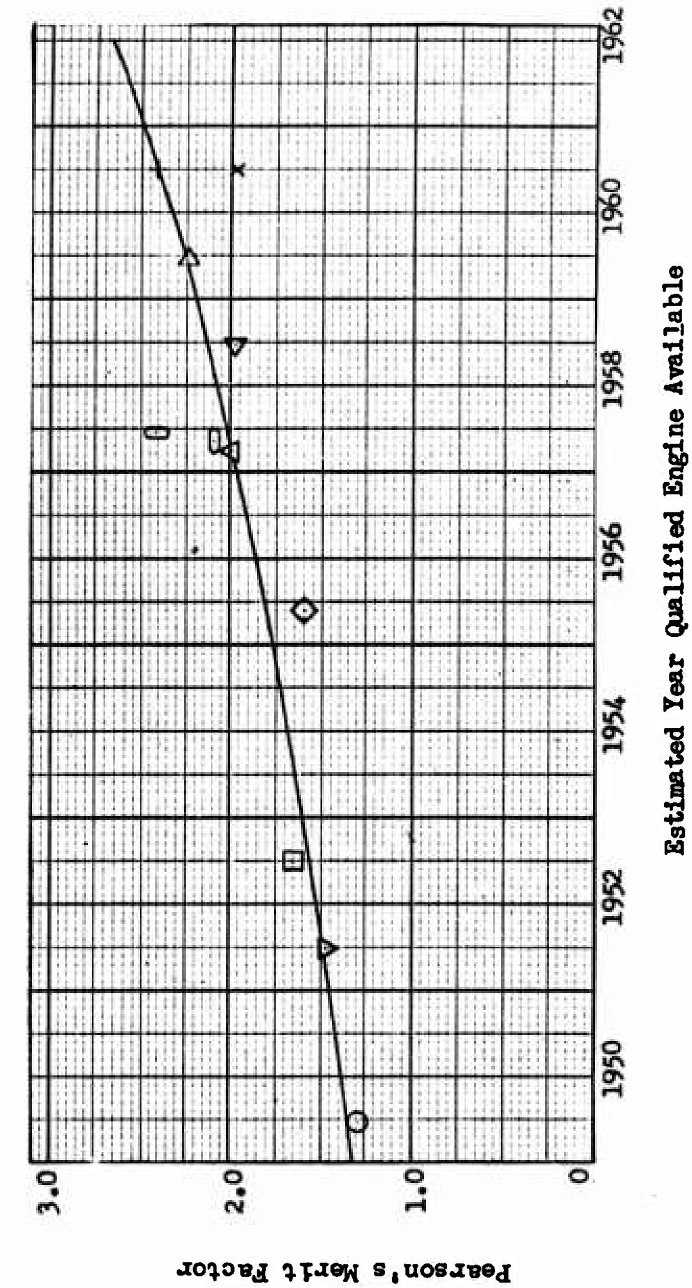
FIGURE 3

PEARSON'S MERIT FACTOR FOR TURBOJET ENGINES

SYMBOLS	MANUFACTURER	MODEL NO.
○	General Electric	J47-GE-15
▽	General Electric	J47-GE-23
□	General Electric	J73-GE-3
◇	Curtiss-Wright	J65-W-6
△	Pratt & Whitney	J75-24
⬭	Westinghouse	PD33-1

SYMBOLS	MANUFACTURER	MODEL NO.
⬭	General Electric	J79-216
◁	Westinghouse	PD33-2
▷	General Electric	J79-207
×	Pratt & Whitney	J52 A/B
+	Pratt & Whitney	J52



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III. DESIGN STUDIES OF SIX VTOL CONFIGURATIONS

Final performance and weight estimates are presented in Reference (2) for the six VTOL aircraft found most promising for the military transport mission. The following six configurations were determined to be most suitable for fulfilling the mission requirements at speeds of 300 mph or greater:

1. Tilt-Wing Propeller
2. Tilting Ducted Propeller
3. Vectored Lift
4. Special Hovering Turbojet
5. Vertodyne
6. Vectodyne

The performance analysis used in the preparation of the data presented throughout this section follow accepted fixed wing methods. The only exception is the method of analysis used for the Vectodyne which employs the Aerodyne principle and is discussed further in Reference (2).

Weights and performance, as summarized in Table V, indicate the first three configurations have approximately equal capability at the specified cruising speed of 300 mph with the vectored lift design resulting in a higher gross weight because of its relative inefficiency for VTOL operation. The latter three configurations, considered most promising for high speeds, give an indication of the gross weight growth accompanied with the combination of VTOL capabilities and increased forward speed potential. It can be seen that the Special Hovering Turbojet does have relatively low forward flight performance as a result of the minimum number of engines installed for forward thrust. It was felt that the maximum forward speed requirement of 375 mph should be sacrificed for this concept, since all other mission requirements were met with the chosen power plants. The 375 mph speed could be met simply by installing a forward flight power package capable of greater thrust with a corresponding increase in the normal gross weight.

The Vertodyne, from a gross weight point of view, appears more promising than the Vectodyne for this particular mission with the former being penalized considerably for cruise at 10,000 feet. Because of its large wing area, the Vertodyne is, of course, more suitable to cruising at altitudes higher than the mission requirement.

TABLE V - SUMMARY OF PERFORMANCE AND WEIGHTS

	Units	TILT-WING PROPELLER	TILTING DUCTED PROPELLERS	VECTORED LIFT	SPECIAL HOVERING TURBOJET	VERTODYNE	VECTODYNE
							
WEIGHTS:							
GROSS WEIGHT	Lbs.	88899	93270	111313	107286	113958	121790
WEIGHT EMPTY	Lbs.	60037	62860	78863	51506	66910	72380
USEFUL LOAD	Lbs.	28862	30410	32450	55780	47048	49410
CREW	Lbs.	600	600	600	600	600	600
PAYLOAD	Lbs.	8000	8000	8000	8000	8000	8000
FUEL	Lbs.	18120	19690	21320	44750	37510	37950
HOVERING & WARM UP	Lbs.	1850	1850	2480	12500	3725	2785
CRUISE, CLIMB & RESERVE	Lbs.	16270	17840	18840	32250	33785	35165
ENGINE OIL	Lbs.	300	300	400	1360	300	450
XMSN OIL	Lbs.	460	460	300	--	300	360
TRAPPED LIQUIDS	Lbs.	432	390	580	1020	288	650
WATER (FOR INJECTION)	Lbs.	900	920	1200	0	0	1350
MISCELLANEOUS	Lbs.	50	50	50	50	50	50
POWER PLANT:		Allison 550-B1	Allison 550-B1	Allison 550-B1	General Electric J-85	General Electric J-79	Allison 550-B1
NUMBER		6	6	8	68 (60-hover 8-fwd.)	4	9
TYPE		Turboprop	Turboprop	Turboprop	Turbojet	Turbojet	Turboprop
TAKE-OFF PER ENGINE (DRY)		5168 SHP	5168 SHP	5168 SHP			5168 SHP
MILITARY PER ENGINE (DRY)		5168 SHP	5168 SHP	5168 SHP	2450 Lbs.	10000 Lbs.	5168 SHP
NORMAL PER ENGINE (DRY)		4590 SHP	4590 SHP	4590 SHP	2000 Lbs.	9700 Lbs.	4590 SHP
PERFORMANCE:							
MAXIMUM FORWARD SPEED							
S.L. ALTITUDE	mph	436	424	450	364	506	450
10000' ALTITUDE	mph	440	424	455	347	500	460
CRUISE SPEED							
S.L.	mph	300	300	300	300	400	345
10000'	mph	300	300	300	300	400	405
MAXIMUM R/C AT SEA LEVEL	MRP Ft/Min	7100	6660	7600	800	3660	5850
MAXIMUM R/C AT 10000'	Ft/Min	5900	5600	6400	320	2550	3650
TIME S.L. TO 10000'	Min.	1.54	1.63	1.43	17.7	3.40	2.11
SERVICE CEILING (100 fpm)	Ft.	43000	42200	39800	13600	37000	24000
HOVERING CEILING @ 95°F	Ft.	6000 (1)	6000 (1)	6000 (1)	6000	6000	6000 (1)
RADIUS OF ACTION (2)	S. Miles	425	425	425	425	425	425

NOTES: (1) With water injection
(2) Mfg's SFC increased 5% - 2 Mins W/U @ MRP - 5 Mins Hovering @ Radius Midpoint - 10% Reserve

The summary of weights and performance is shown for the basic transport mission. A more complete picture of the performance capability of each configuration can be found in the Characteristics Charts presented in Reference (2).

TABLE VI - SUMMARY OF GROUP WEIGHT STATEMENTS

	TILT-WING PROPELLER	TILTING DUCTED PROPELLER	VECTORED LIFT	SPECIAL HOVERING TURBOJET	VERTODYNE	VECTODYNE
ROTOR GROUP	8736	11155	11328	--	4580	6990
WING GROUP	7275	6940	11650	7060	10600	9100
TAIL GROUP	3150	3150	3780	3750	3960	4200
BODY GROUP	6746	7480	7890	8030	8130	8640
ALIGHTING GEAR GROUP	4500	4050	5940	4820	5080	5400
ENGINE SECTION	2710	4530	6030	1620	4730	4750
POWER PLANT	16270	20435	27800	20935	24305	27420
ENGINE	12060	12060	6080	15246	12600	6170
ENGINE ACCESSORIES	910	910	880	820	800	1270
POWER PLANT CONTROLS	120	120	160	510	160	180
STARTING SYSTEM	680	680	900	1350	400	900
COOLING SYSTEM	150	150	200	--	1400	600
LUBRICATION SYSTEM	1340	1340	1780	1320	800	2010
FUEL SYSTEM	1010	1050	1290	1690	1340	1700
TRANSMISSIONS	3470	3040	4640	--	1705	3720
SHAFTING	2210	1085	1870	--	1180	870
FIXED EQUIPMENT	4970	5160	4445	5290	5525	5880
INSTRUMENTS	270	270	360	890	240	300
FLIGHT CONTROLS	2200	2250	1425	1575	2650	2880
HYDRAULIC SYSTEM	350	370	390	430	435	480
ELECTRICAL SYSTEM	850	850	850	1050	850	850
COMMUNICATION SYSTEM	300	300	300	300	300	300
FURNISHINGS	800	800	800	800	800	800
MISCELLANEOUS	200	320	220	245	250	270
WEIGHT EMPTY	60037	62860	78863	51506	66910	72380
USEFUL LOAD	28862	30410	32450	55780	47048	49410
CREW	600	600	600	600	600	600
TRAPPED LIQUIDS	432	390	580	1020	288	650
ENGINE OIL	300	300	400	1360	300	450
TRANSMISSION OIL	460	460	300	--	300	360
FUEL	18120	19690	21320	44750	37510	7950
CARGO	8000	8000	8000	8000	8000	8000
MISCELLANEOUS	50	50	50	50	50	50
WATER	900	920	1200	--	--	1350
GROSS WEIGHT	88899	93270	111313	107286	113958	121790

TABLE VII - SUMMARY OF DIMENSIONAL DATA

	TILT WING	TILTING DUCTED PROPELLERS	VECTORED LIFT	SPECIAL HOVERING TURBOJET	VERTODYNE	VECTODYNE
General						
Length (Overall)	84 ft 9 in	84 ft 9 in	84 ft 6 in	92 ft 0 in	91 ft 0 in	85 ft 0 in
Fuselage Width (Max)	13 ft 6 in	13 ft 6 in	13 ft 6 in	13 ft 6 in	13 ft 6 in	13 ft 6 in
Height (to Top of Vertical Fin)	37 ft 0 in	37 ft 0 in	32 ft 0 in	35 ft 0 in	35 ft 0 in	33 ft 8 in
Wing						
Span	85 ft 6 in	109 ft*	98 ft 6 in	90 ft	106 ft	
Area	1170 sq.ft	1426 sq.ft**	1430 sq.ft	1400 sq.ft	2284 sq.ft	
Aspect Ratio	6.25	8.35	6.79	5.78	4.91	
Taper Ratio	.498	.776	1.0	.250	.335	
Airfoil	2415	2415	2415	63_3-018	63_3-018	
M.A.C.	14 ft 4 in	14 ft 6 in	18 ft	15 ft	24 ft 6 in	
Tail						
Vertical Tail Area	260 sq.ft	260 sq.ft	240 sq.ft	300 sq.ft	240 sq.ft	280 sq.ft
Horizontal Tail Area	320 sq.ft	320 sq.ft	300 sq.ft	300 sq.ft	300 sq.ft	400 sq.ft
Landing Gear						
Tread	13 ft 6 in	14 ft	13 ft 6 in	63 ft 0 in	13 ft 6 in	15 ft 8 in
Wheel Base	24 ft 6 in	27 ft 9 in	32 ft 6 in	35 ft 6 in	26 ft 9 in	24 ft 6 in
Propellers						
Diameter	21 ft 0 in	17 ft 6 in 12 ft 0 in	25 ft 0 in	—	16 ft 8.4 in	18 ft 0 in
Tip Speed	850 fps	850 fps	850 fps	—	900 fps	900 fps
Disc Loading	64.1	131.5	57.6	—	259	

*Over Ducts
**Includes 50% Ducts

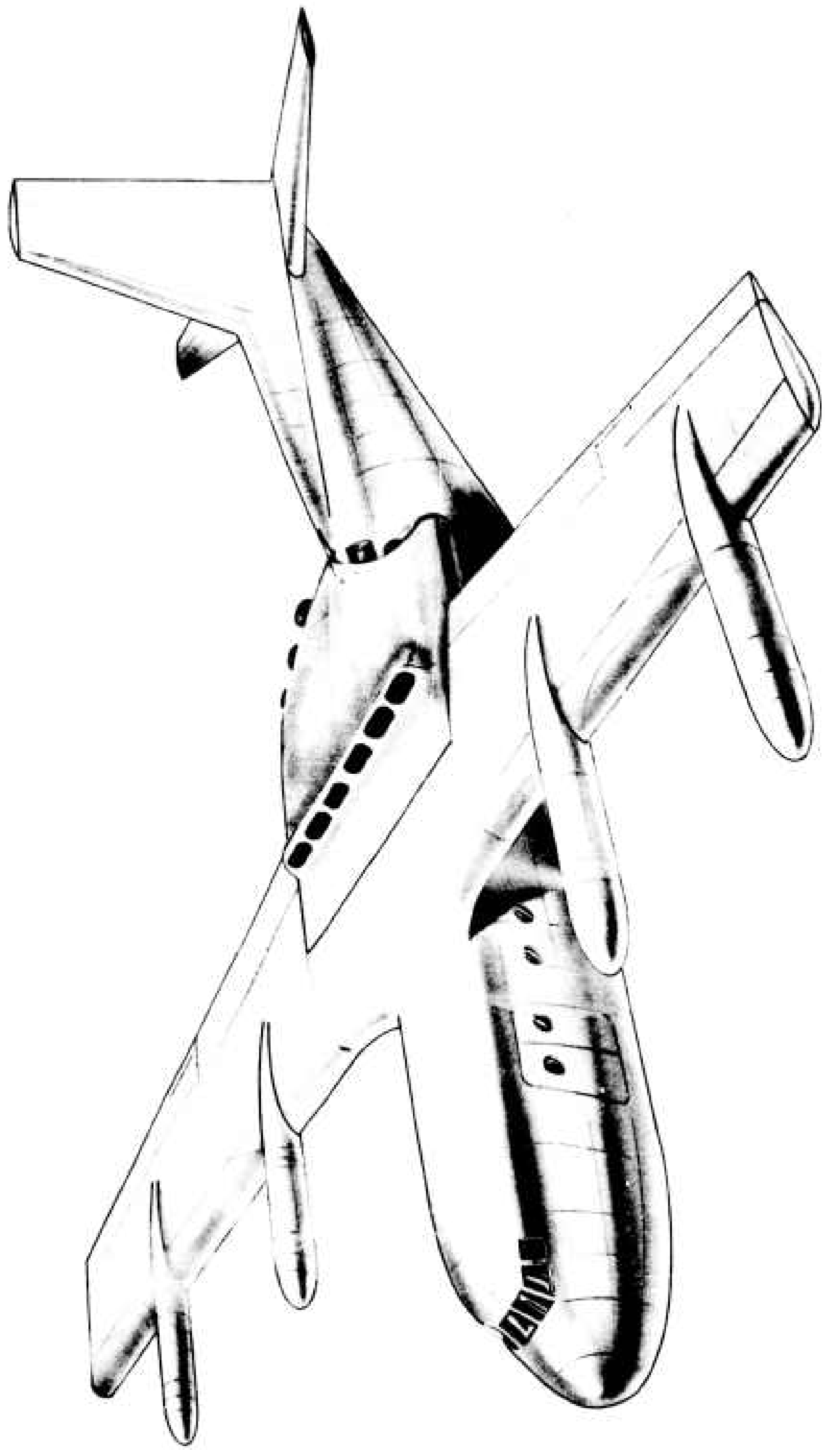

FIG. 4 - TILT WING PROPELLER CONFIGURATION

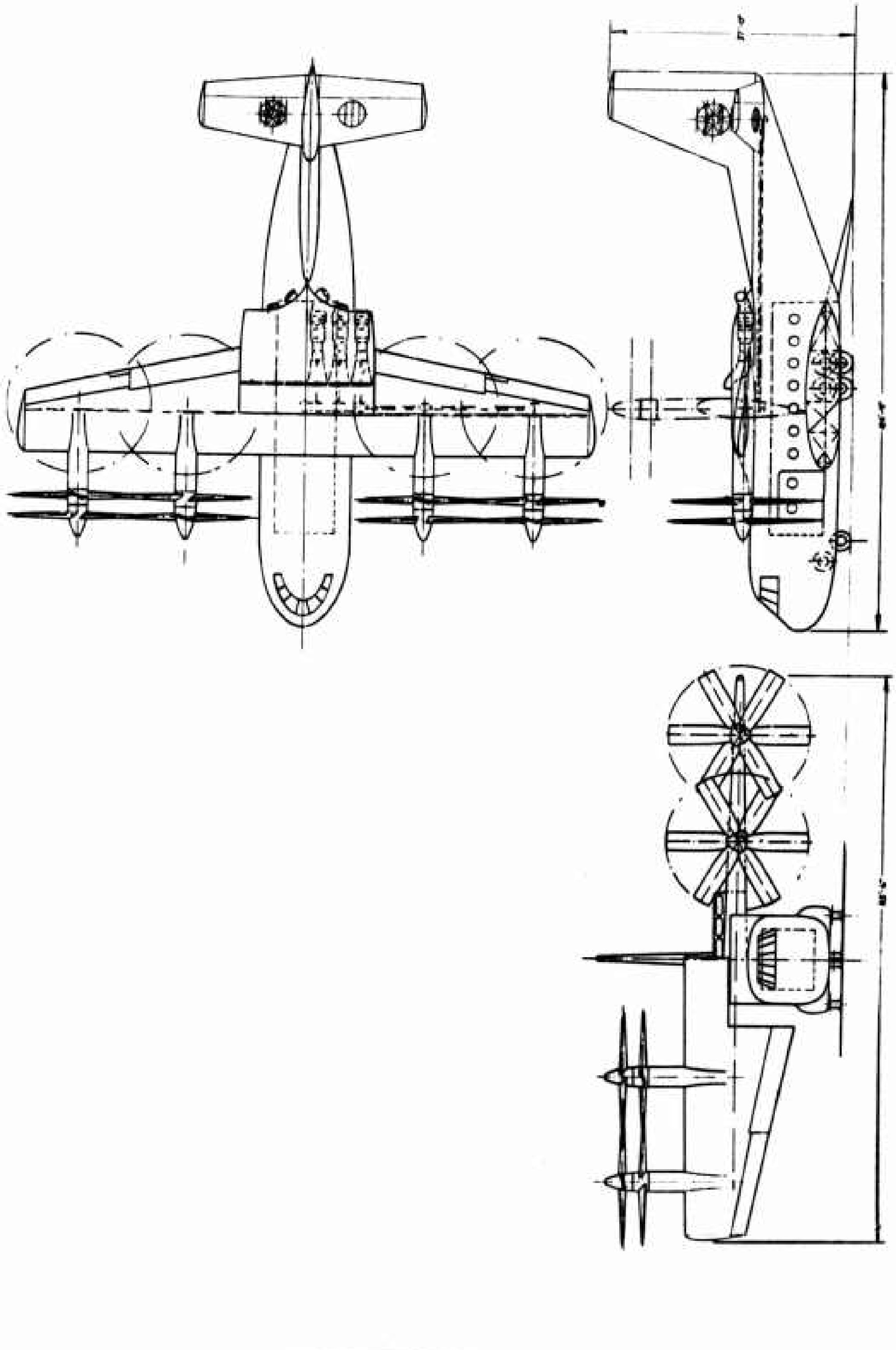

FIG. 5 - TILT WING PROPELLER GENERAL ARRANGEMENT DRAWING

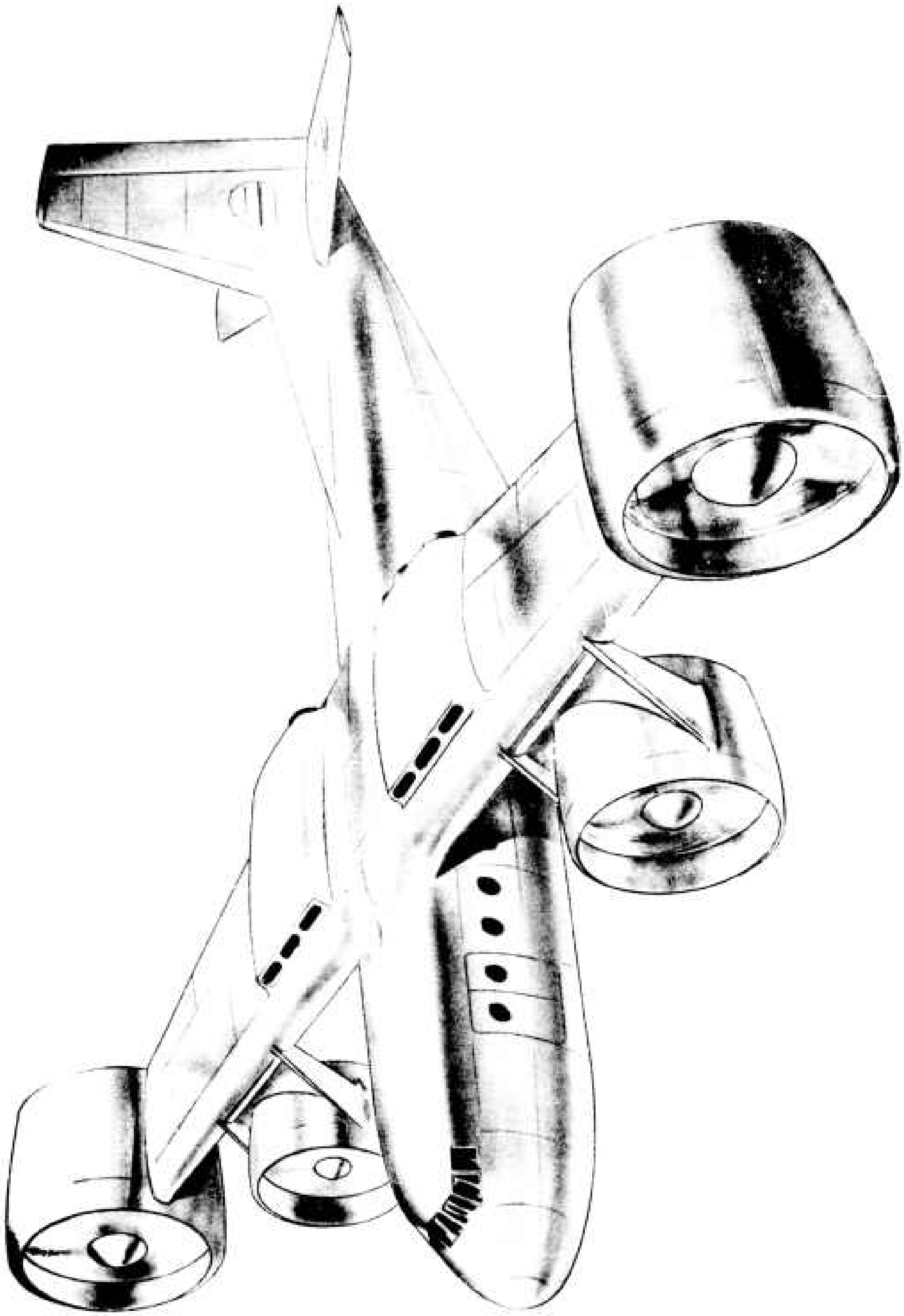

FIG. 6 - TILTING DUCTED PROPELLER CONFIGURATION

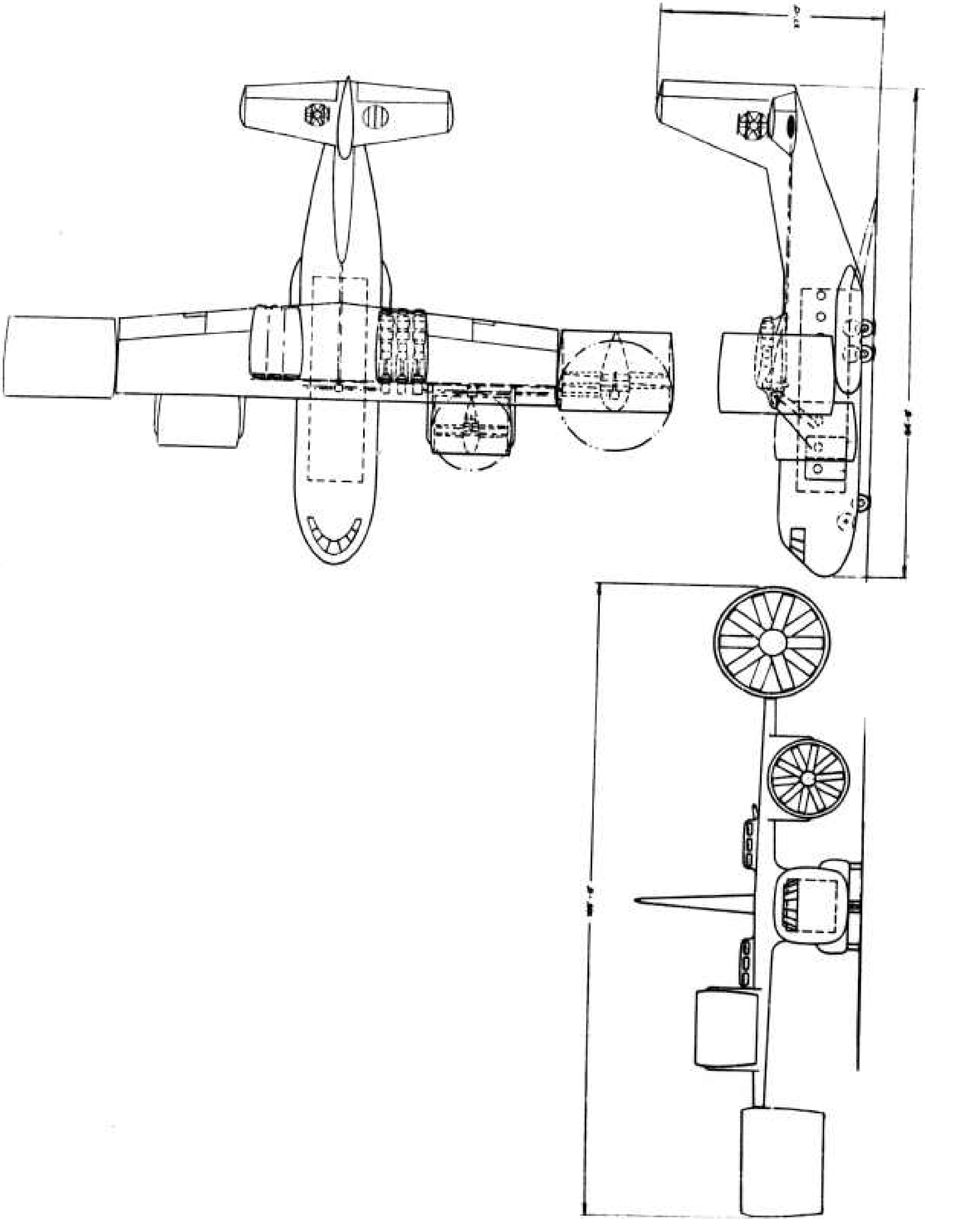

FIG. 7 - TILTING DUCTED PROPELLER GENERAL ARRANGEMENT DRAWING

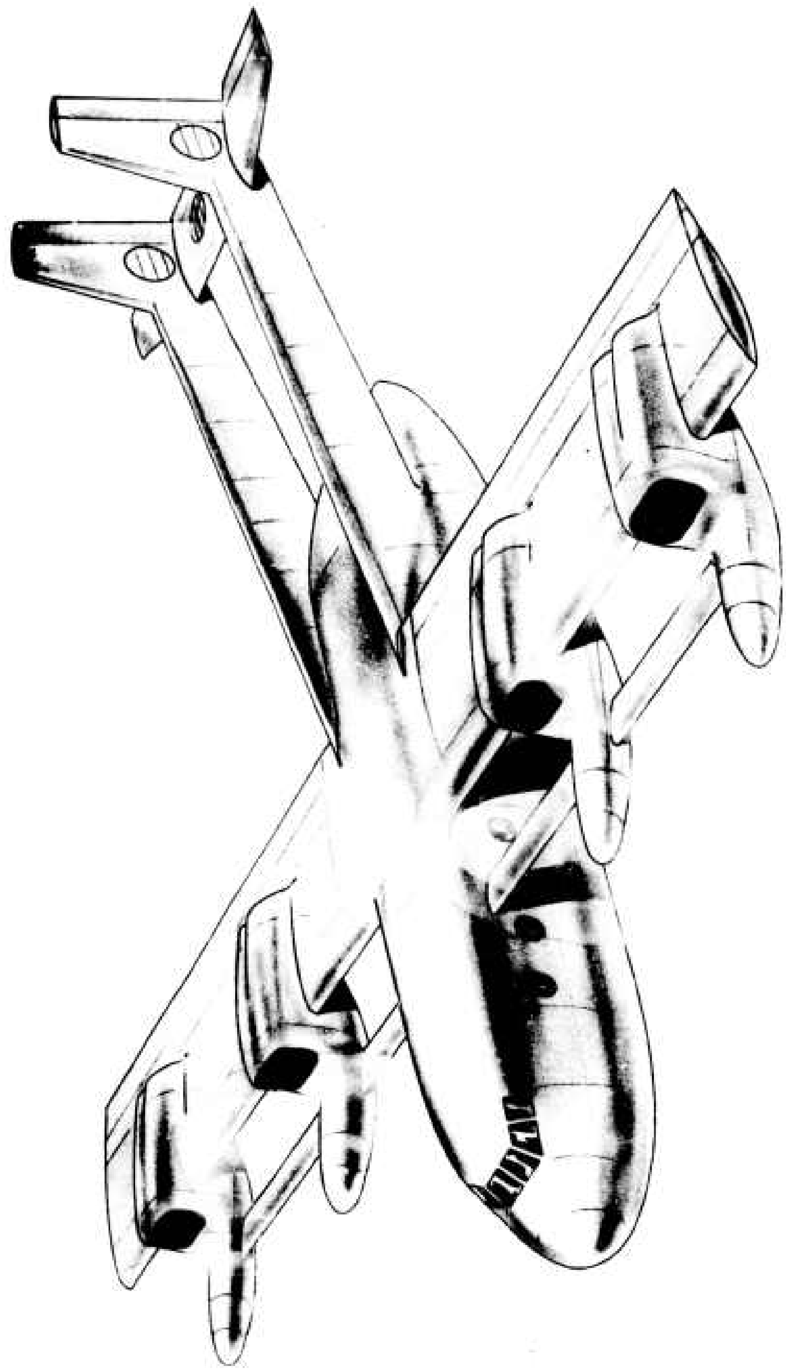

FIG. 8 - VECTORED LIFT CONFIGURATION

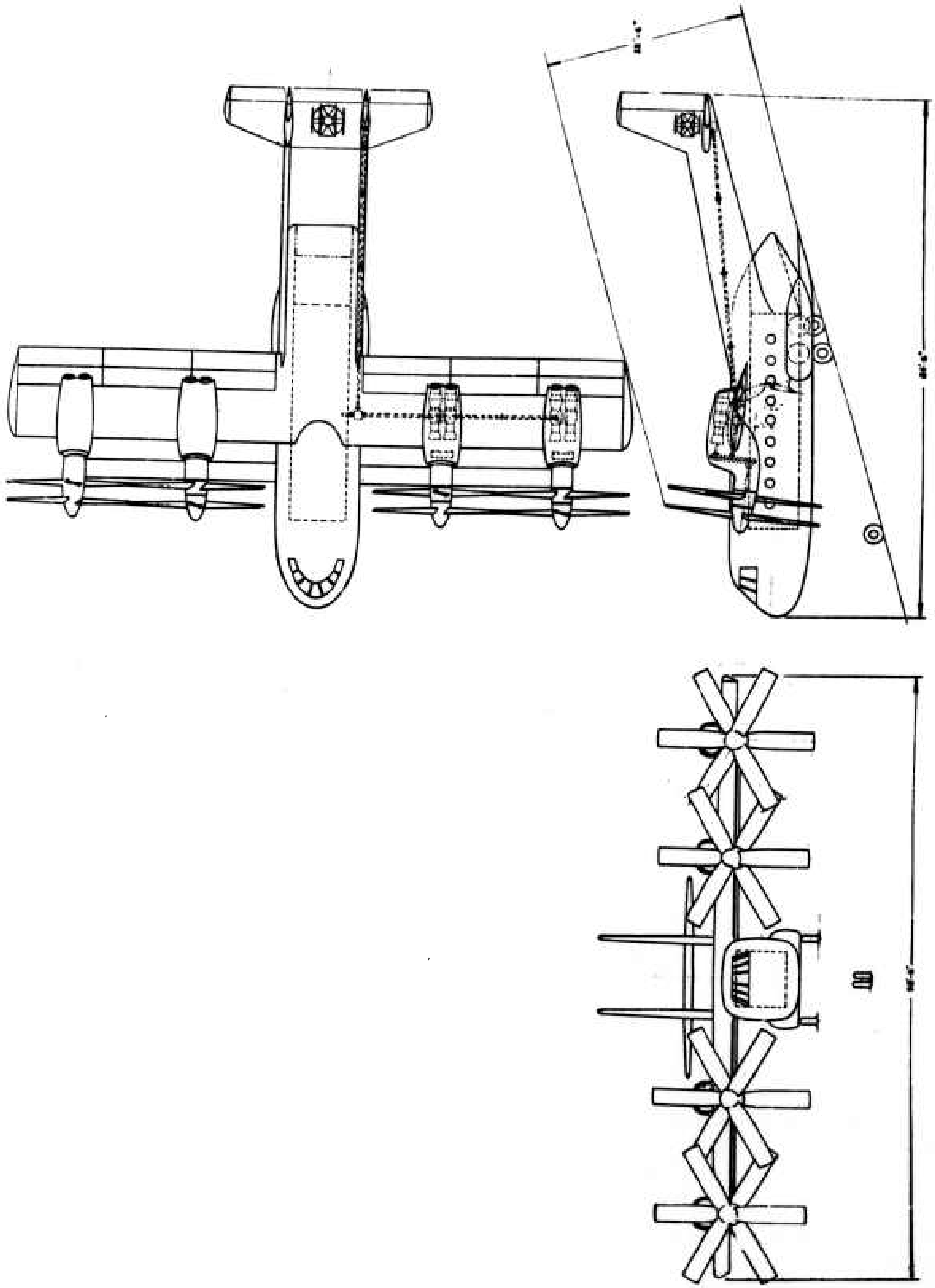

FIG. 9 - VECTORED LIFT GENERAL ARRANGEMENT DRAWING

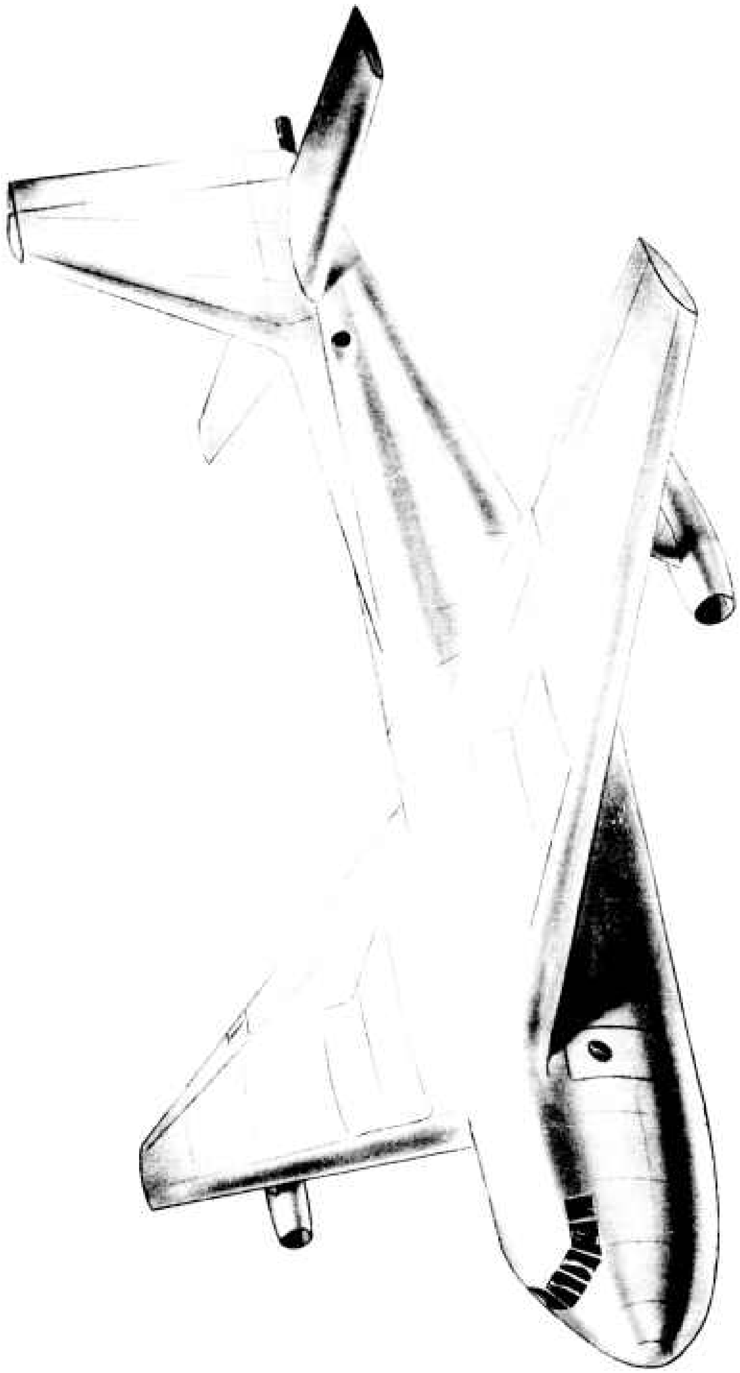

FIG. 10 - SPECIAL HOVERING TURBOJET CONFIGURATION

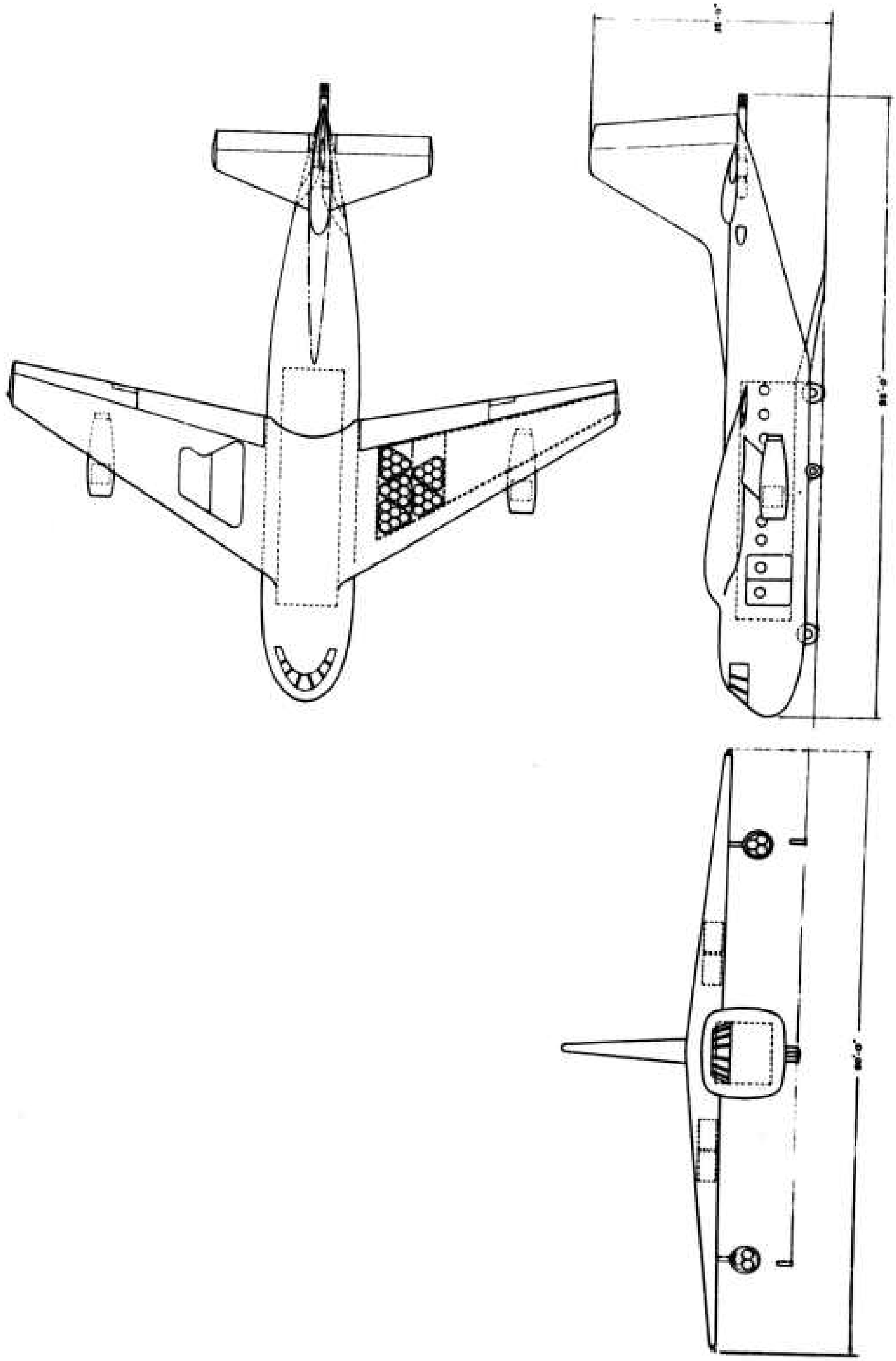

FIG. 11 - SPECIAL HOVERING TURBOJET GENERAL ARRANGEMENT DRAWING

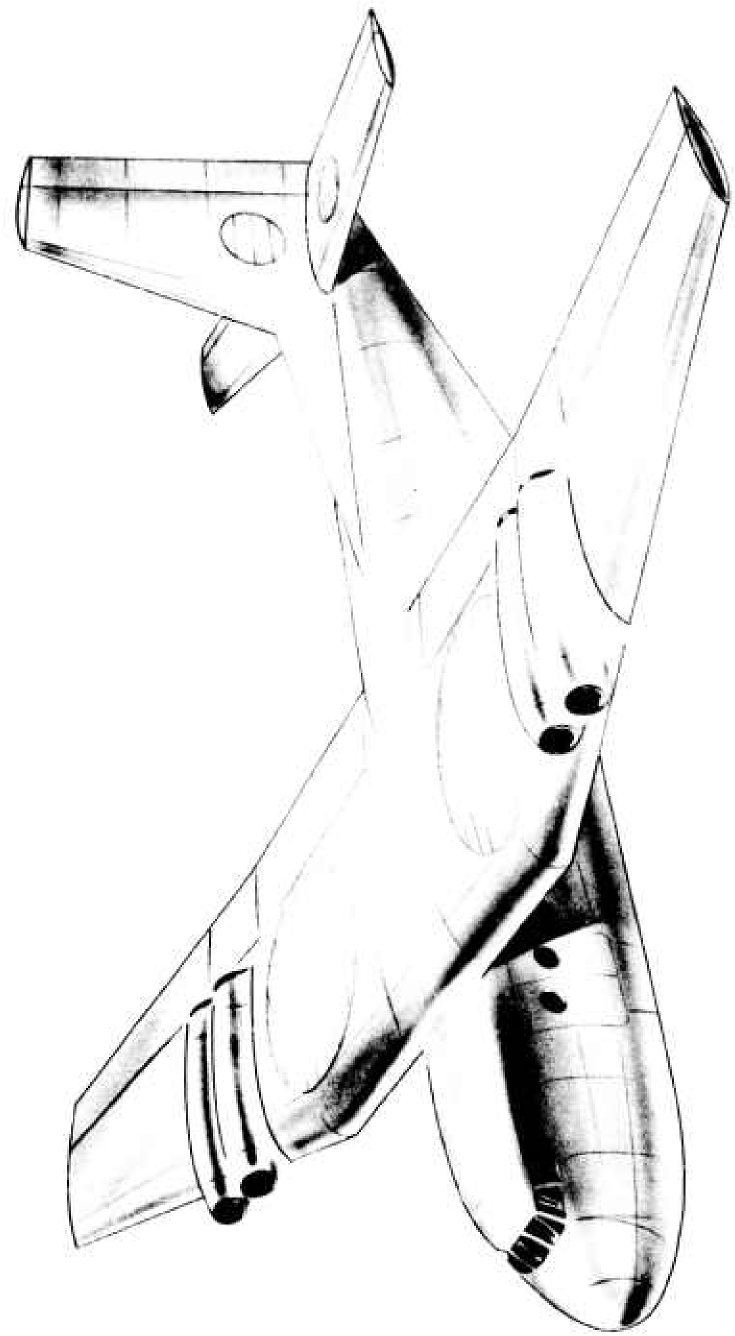

FIG. 12 - VERTODYNE CONFIGURATION

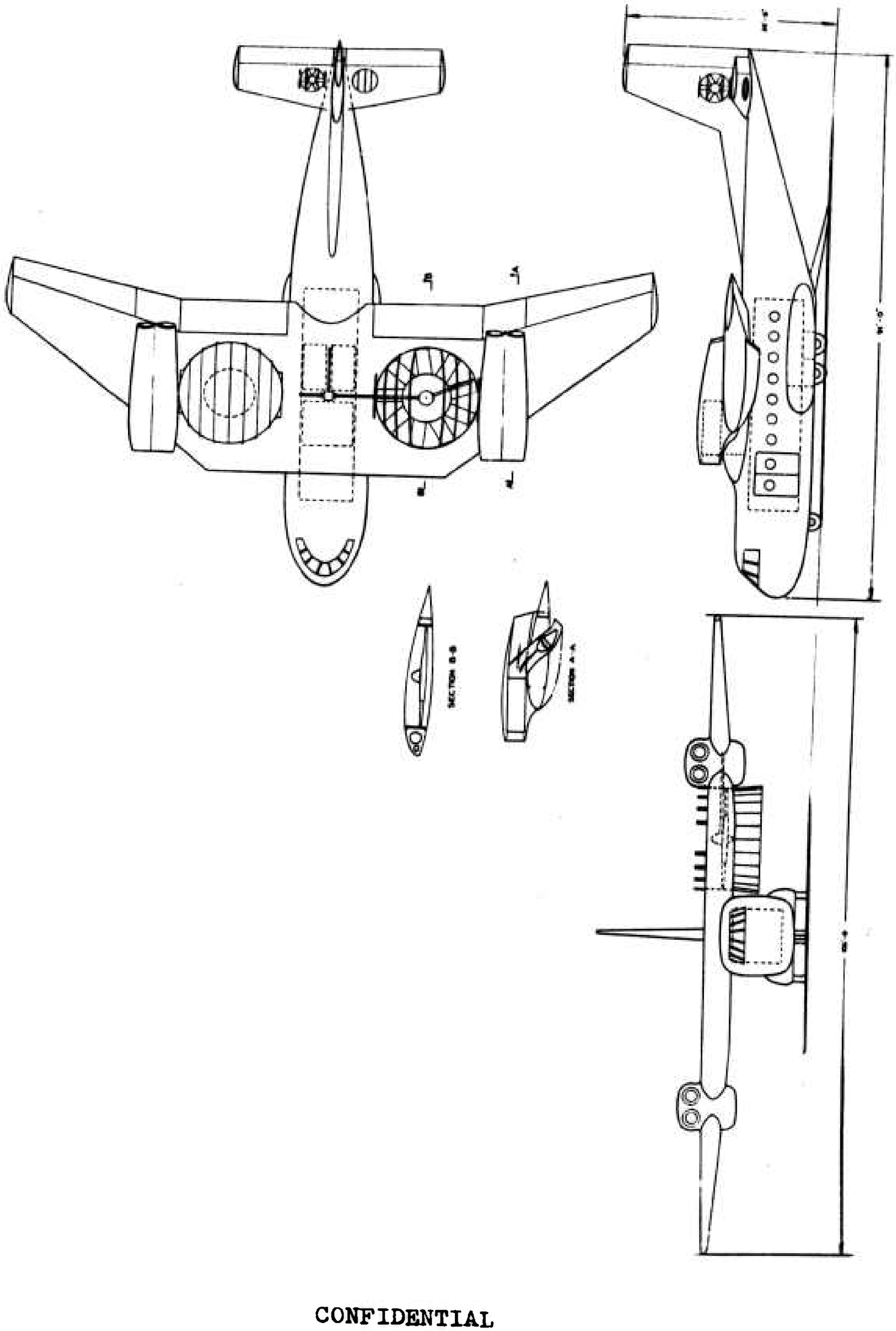

FIG. 13 - VERTODYNE GENERAL ARRANGEMENT DRAWING

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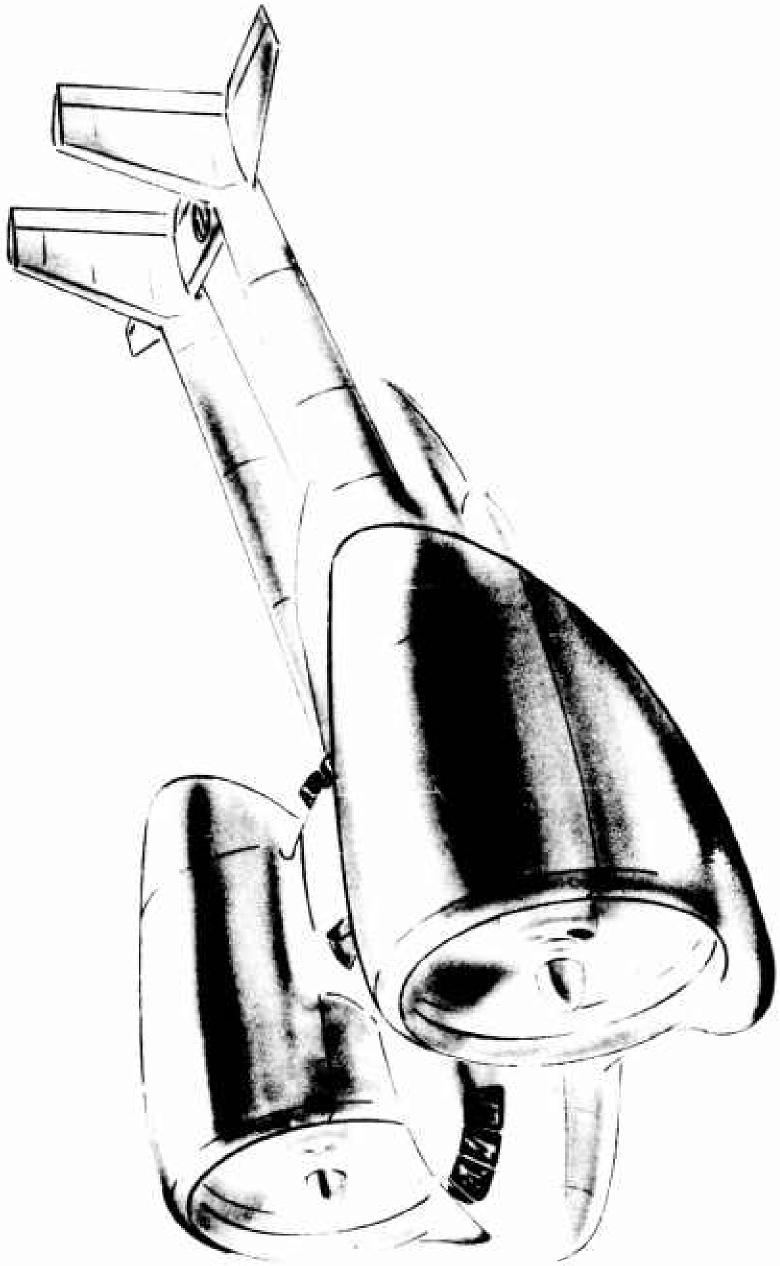


FIG. 14 - VECTODYNE CONFIGURATION

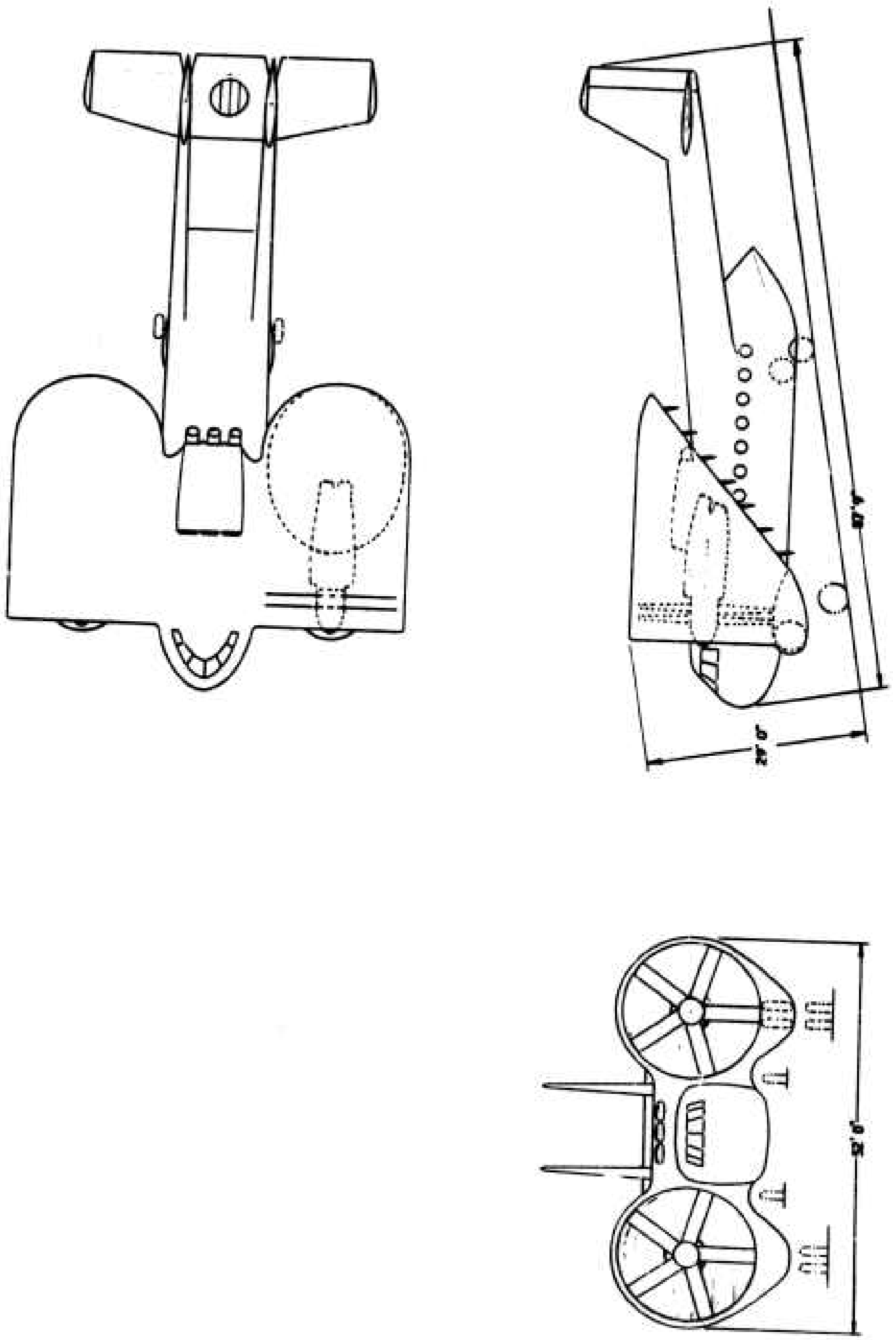


FIG. 15 - VECTODYNE GENERAL ARRANGEMENT DRAWING

IV. DETAILED STUDIES OF THE TILT WING PROPELLER AND VERTODYNE CONFIGURATIONS

The results of the broad comparative parametric study, reported in Reference (1), and the more detailed weight and performance analysis of Reference (5), indicated that for the mission requirements, the Tilt Wing Propeller concept is the optimum VTOL aircraft for cruising speeds of 250 to 350 miles per hour while for higher cruising speeds, the Vertodyne appears to be more suitable. Consequently, these two configurations were selected for further detailed study. Due to the limited scope of the subject contract, the detailed studies were restricted to the analysis of particular items peculiar to each configuration.

An abbreviated summary of the investigated areas is presented along with pertinent figures and illustrations.

A. Propeller Aerodynamics

In Reference (6), the vortex theory of propellers was developed in a manner suitable for the analysis of propellers for tilt-wing VTOL aircraft. Expressions defining the optimum rotor and the optimum propeller are developed which show that a single design will not satisfy both optimums.

From the results of computations performed with an automatic digital computer, it is concluded that in order to obtain good performance from a single design acting as both a rotor and a propeller, the propeller should be designed to operate at a high advance ratio in the airplane state. In addition, depending upon the blade solidity, the design of the propeller with regard to pitch distribution and planform should favor operation as a propeller rather than as a rotor.

This last statement is supported by Figures 16 and 17. The power required to hover using a good rotor and a good propeller is shown in Figure 16 for a large tilt-wing transport of 100,000 lbs. gross weight. The power required for a forward flight as an airplane at 400 fps for an assumed drag of 10,000 lbs. using a good propeller and a rotor are shown in Figure 17. From Figure 17 it can be seen that over the range of values of advance ratios (propeller tip speed/forward speed) considered, the power required required to hover by the propeller for σ (solidity) of 0.3 and 0.5 is at the most only 4% higher than the power required by the optimum rotor. However, from Figure 17, the power required by the rotor in forward flight is at best, 10% higher than that required by the propeller at the higher values of advance ratio and at the lower values of advance ratio, is more than 50% higher than for the propeller.

FIG. 16 - POWER REQUIRED BY OPTIMUM ROTOR AND OPTIMUM PROPELLER TO HOVER EXAMPLE TILT-WING TRANSPORT

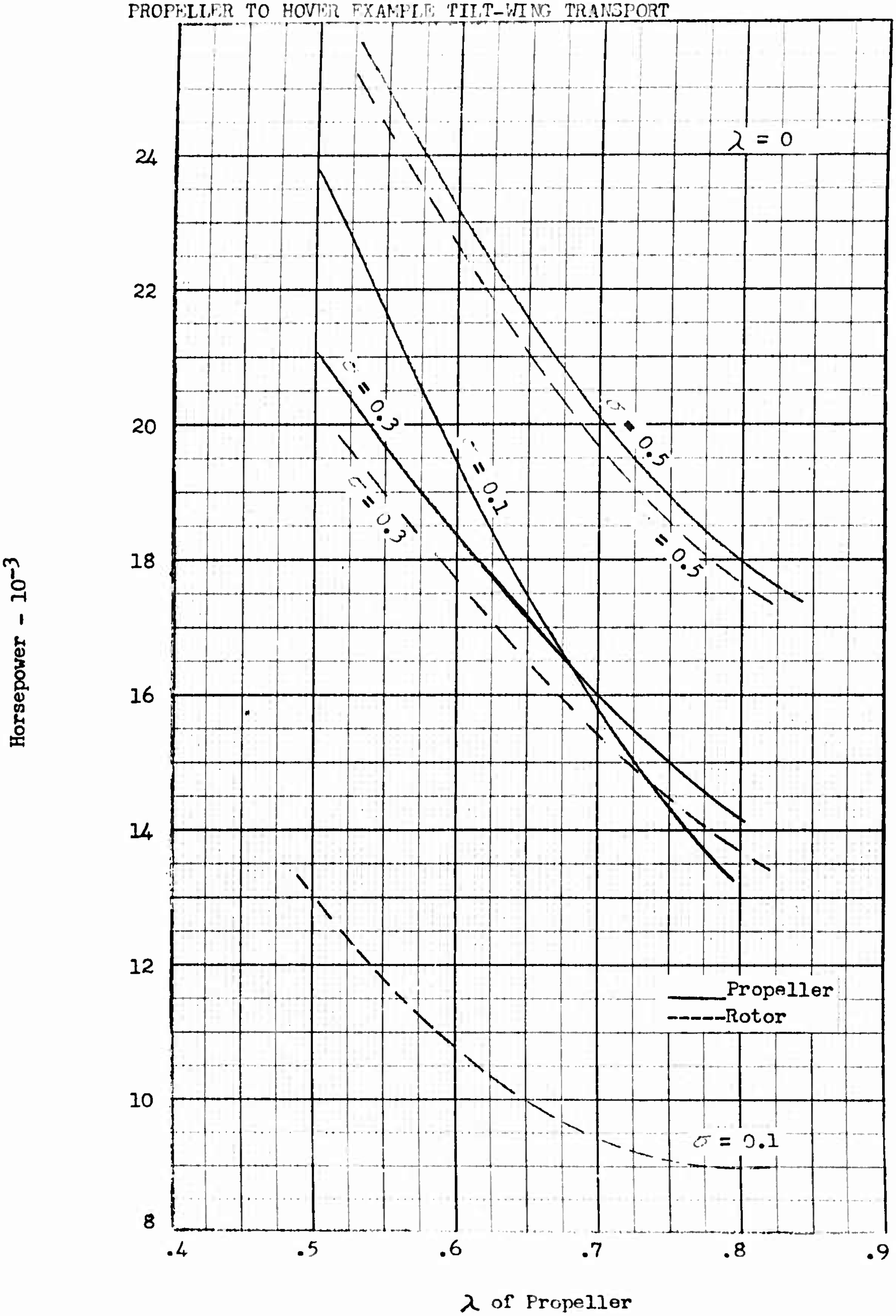
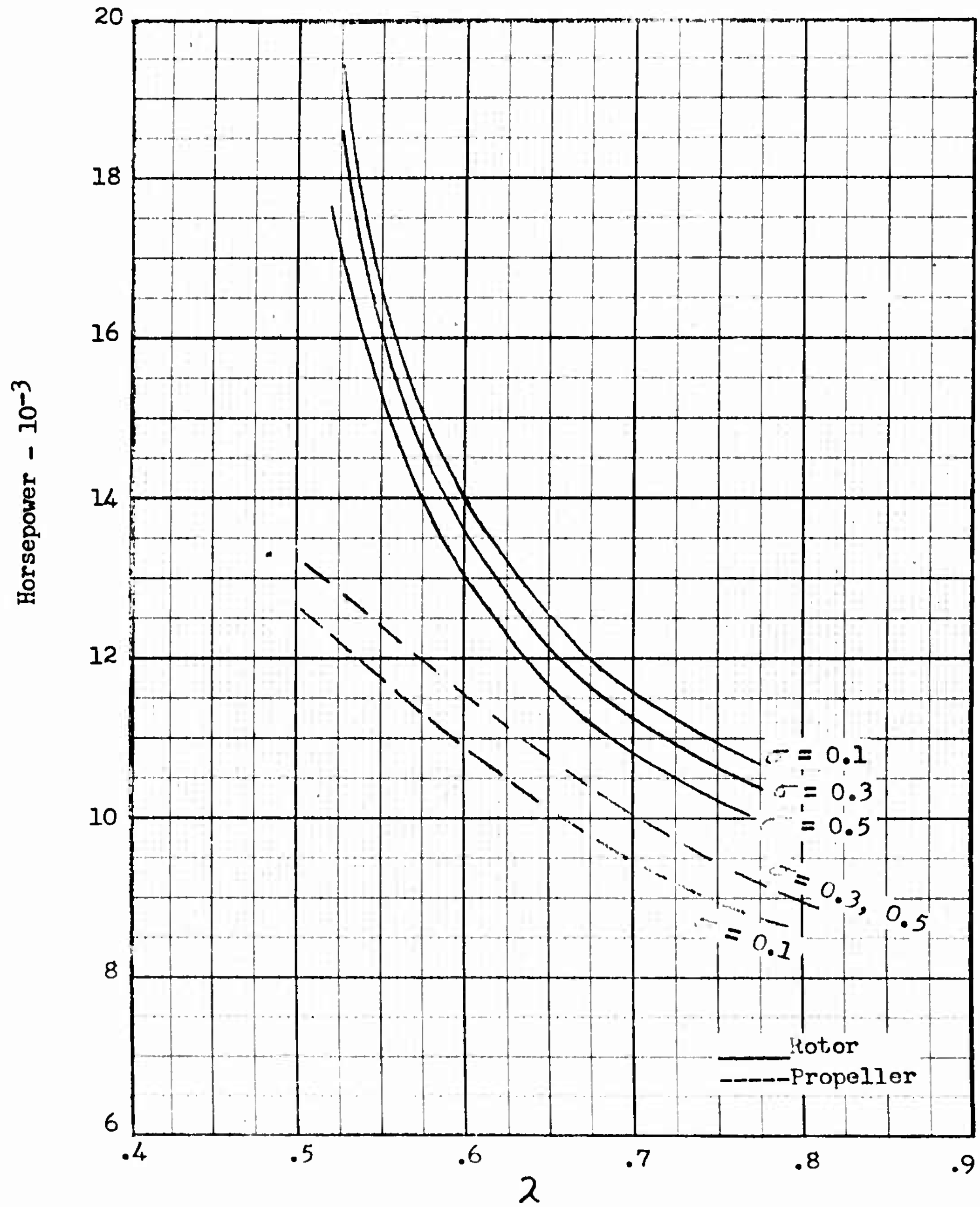


FIG. 17 - POWER REQUIRED BY OPTIMUM ROTOR AND OPTIMUM PROPELLER TO PROPEL THE EXAMPLE TILT-WING TRANSPORT IN FORWARD FLIGHT



B. Unsteady Flight Problems of the Tilting Wing Propeller Aircraft

In Reference (7), two problems of an unsteady nature concerned with the operation of tilt-wing, VTOL aircraft were analyzed. The motion of such an aircraft during its transition from the hovering state to the airplane state or during the reverse procedure was determined. In addition, the behavior of a tilt-wing aircraft following a partial or complete power failure in the hovering state was investigated.

The transition analysis disclosed no apparent aerodynamic problems which might prohibit such a procedure. In going from the hovering state to the airplane state, the thrust required to maintain a constant altitude was found to decrease steadily for a reasonable time of transition. This fact is illustrated in Figure 18, which presents, for three different transition times, the thrust required to maintain a constant altitude for a typical tilt-wing transport. For the rapid transition of 10 seconds duration, the required thrust is seen to increase initially before dropping off, while for the longer times of transition, it decreases steadily.

The shortest interval of time in which the transition can be accomplished was found to be limited apparently by the maximum forward acceleration which can be tolerated. Figure 19 presents the maximum accelerations which were calculated for a typical light tilt-wing aircraft and for a tilt-wing transport as a function of the transition time. From the standpoint of passenger comfort, the transition time for the transport should probably not be less than 25 seconds.

The investigation of vertical descent following a power failure for this type of aircraft showed the importance of multi-engine reliability. Because of the high disc loadings to be employed with this type of aircraft, the vertical descent velocity without any power is very high. For example, for a typical light aircraft which was investigated, the vertical descent velocity at ground contact from an altitude of 50 feet was never less than approximately 75% of the free-fall velocity regardless of the collective pitch action taken after failure.

FIG. 18 - THRUST REQUIRED DURING TRANSITION FOR THE TILT WING TRANSPORT TO MAINTAIN CONSTANT ALTITUDE

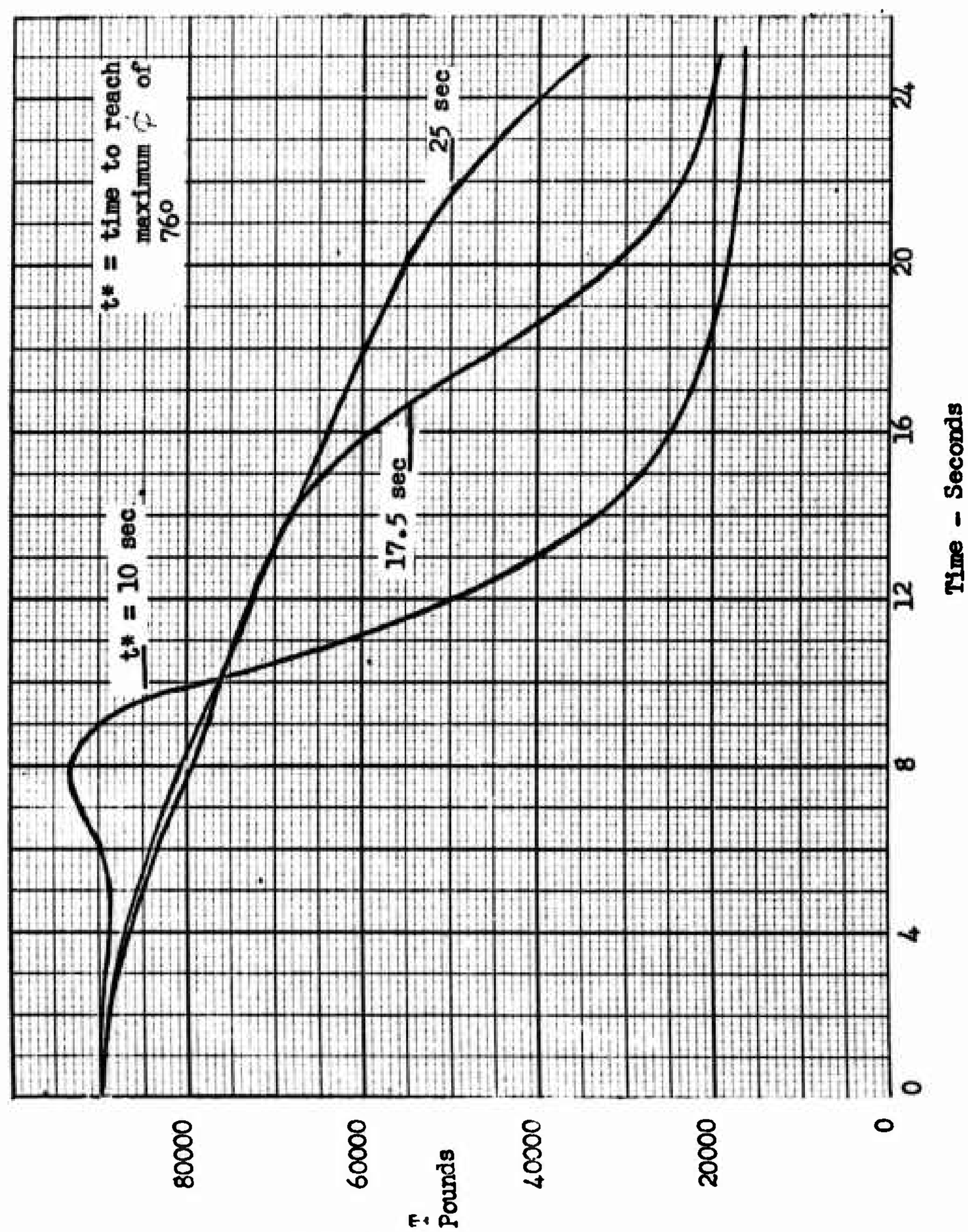
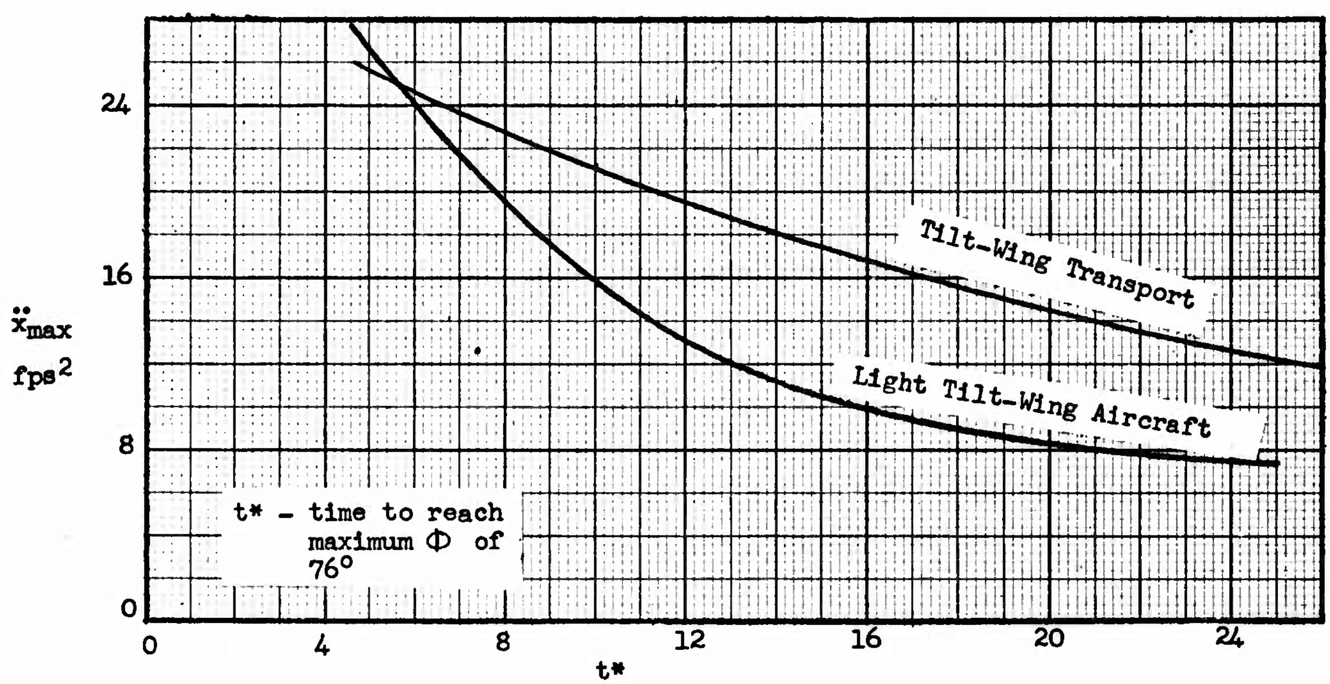


FIG. 19 - MAXIMUM ACCELERATIONS CALCULATED FOR THE LIGHT TILT-WING AIRCRAFT AND THE TILT-WING TRANSPORT DURING TRANSITION



C. Preliminary Wing Weight Determination

Preliminary studies of Reference (8), indicated that two VTOL transport type aircraft configurations required detailed wing weight studies to aid in determination of optimum VTOL types. These configurations are: (1) a tilting wing design, where wing and propellers rotate approximately 90° about a lateral tilt axis for vertical flight, and (2) a vectored lift design, where vertical flight is attained by deflecting the propeller slipstream downward, with a compound flap arrangement.

In final design, the main structural difference between these two types will be the wing configuration. It was important, therefore, to estimate a reasonably accurate wing weight, for a wide range of design parameters.

Gross weight was varied from 60,000 to 120,000 pounds; aspect ratio from 5 to 12 and span loading was varied from 800 to 1600 pounds per foot. For the tilt-wing, wing taper ratio was varied from .5 to 1.0. A taper ratio of 1.0 was assumed for the vectored lift wing arrangement.

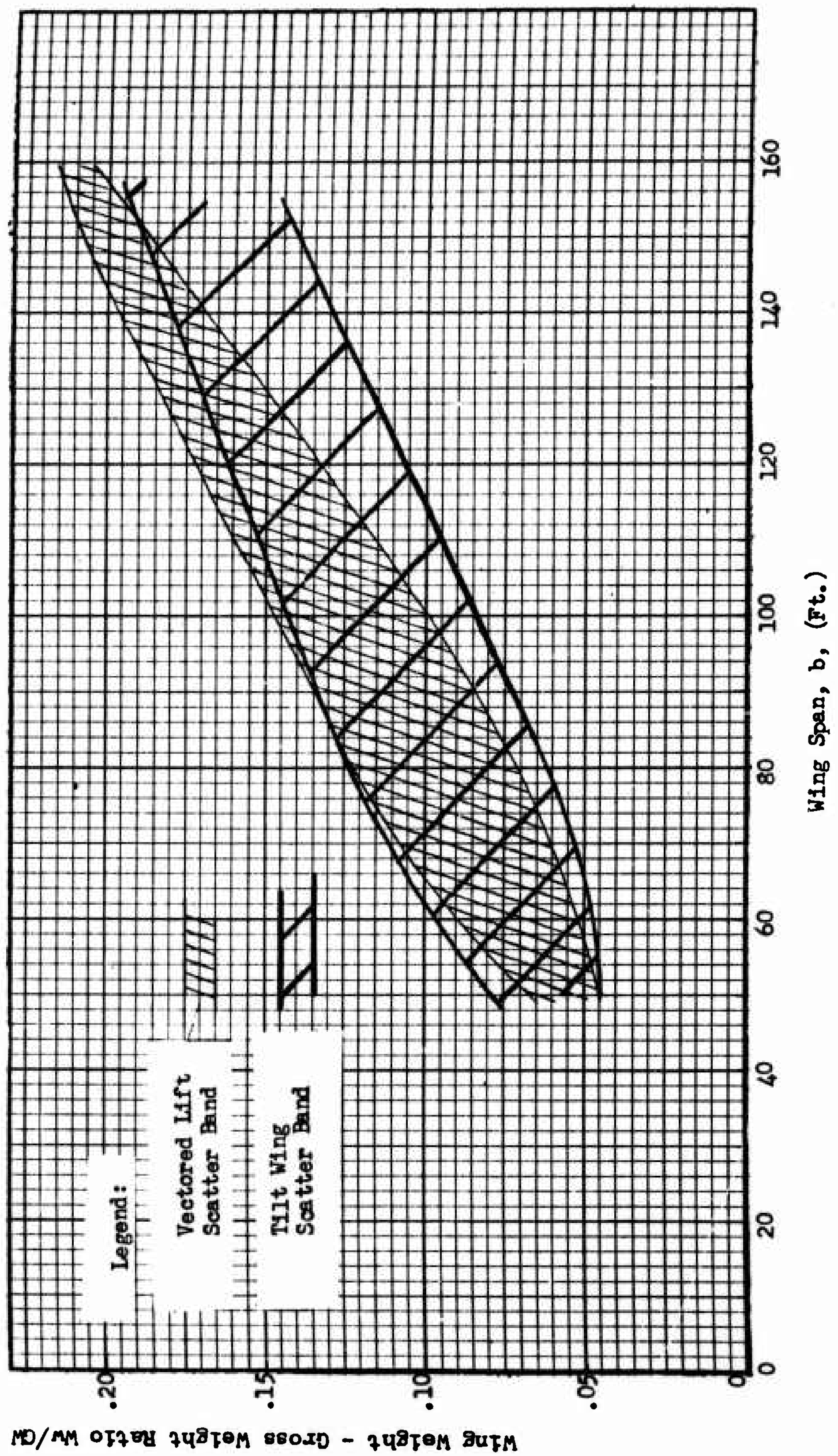
As shown in Figure 20, the tilt wing design lends itself to more efficient wing structural design that does the vectored lift. It is, however, important to note that the weight differential is not large over the greater portion of range of parameters investigated. Therefore, the structural weight of the wing is not an important consideration in the choice between the tilt wing and vectored lift designs.

A detailed discussion of this phase of the investigation can be found in Reference (12).

D. STOL Capabilities of the Tilt Wing Propeller

A study, Reference (9), was undertaken to determine the potential increase in gross weight for the Tilt Wing Propeller VTOL transport design when operating as a STO aircraft (running take-offs). The ground roll distance and total distance required to clear a 50 foot obstacle was obtained as a function of take-off gross weight. Calculations were made for 45, 35 and 25 degrees of wing tilt. During the ground roll distance and throughout the climb phase of the operation, the wing tilt was held constant.

FIG. 20 - WING WEIGHT ENVELOPE CURVES FOR VECTORED LIFT & TILT WING



At a pressure altitude of 6,000 and 95°F ambient day, the VTOL design gross weight is approximately 90,000 pounds. With 45° of wing tilt and a ground run of 340 feet, the take-off gross weight can be increased to 96,000 pounds. With 35° of tilt and 750 feet of ground run, the gross weight can be increased to 103,500 pounds. Finally, for 25° of wing tilt, a gross weight of 120,000 pounds is obtained for a ground roll distance of 1,810 feet.

For sea level standard day operation, vertical take-off is possible at a gross weight of 104,000 pounds. For 45° of wing tilt, this value can be increased to 110,000 pounds and the aircraft can take-off in 260 feet. For 35° of tilt and 480 feet of ground distance, the take-off gross weight is 112,000 pounds. For 25° of wing tilt, a gross weight of 142,000 pounds is obtained for a ground roll distance of 2000 feet.

It should be noted that the aircraft was designed primarily for VTOL operation with no basic consideration for STO capabilities. Consequently, the total distance required to clear a 50 foot obstacle increased rapidly due to the high wing loadings. With some changes in basic design parameters, it is believed the STO performance could be substantially increased incurring some penalty in VTOL performance. This problem of compromise between VTOL and STOL performance should be subjected to a more thorough analysis, taking into consideration not only basic design variables, but also the anticipated operational requirements.

E. Effect of Performance Criteria on the Optimum Design of the Tilt Wing Propeller and Vertodyne

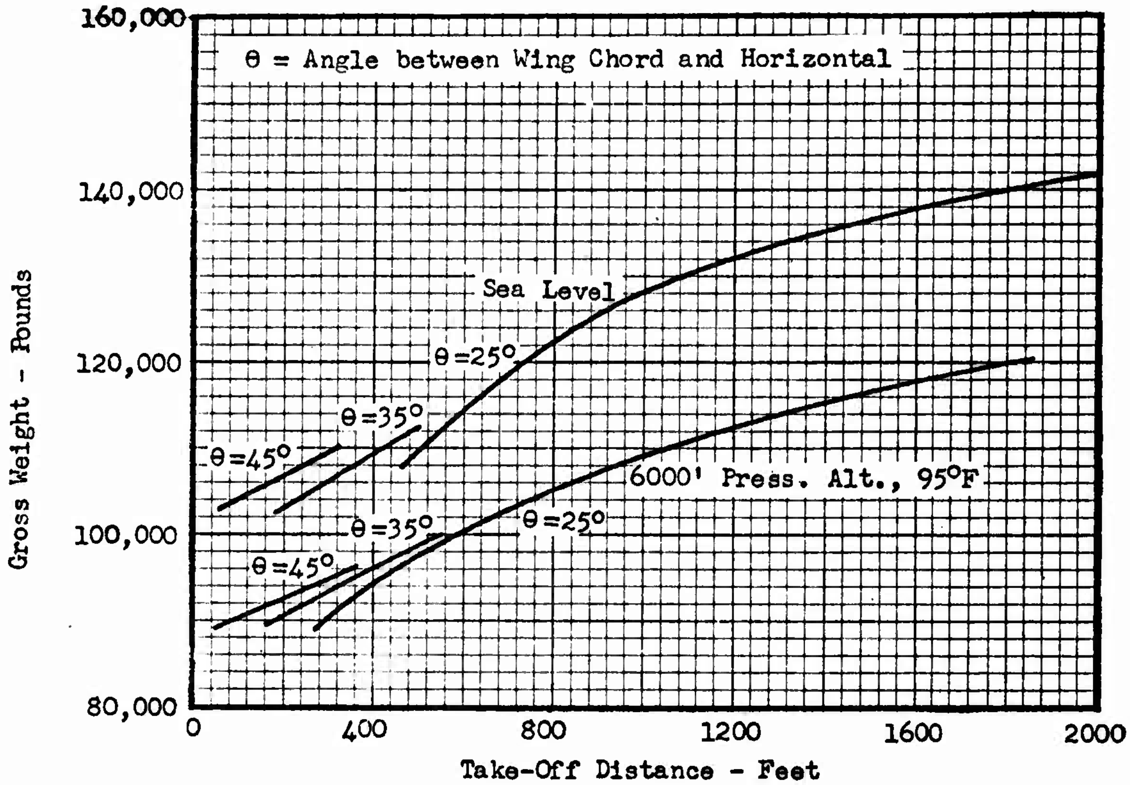
In order to more thoroughly investigate the effects of various performance criteria on the optimum design of VTOL aircraft, a parametric study (Reference 3), suitable for solution on IBM electronic computers was made for the Tilt Wing Propeller and Vertodyne aircraft. The effect of hovering ceiling, hovering time and cruise altitude on the minimum gross weight of each aircraft was determined.

Each aircraft is designed for a radius of action of 425 statute miles carrying an outbound payload of 8,000 pounds and an inbound payload of 4,000 pounds. Power plant performance and weight trends used throughout this study reflect the anticipated state of art for the year 1962.

TILT WING PROPELLER

FIG. 21 - TAKE-OFF DISTANCE VS. GROSS WEIGHT

(GROUND RUN DISTANCE)



Although the combined effect of the various performance variables must be considered in an overall evaluation, the effect of particular criterion on the optimum size can be determined approximately while keeping the remaining variables constant. On this basis, hovering ceiling has the greatest percentage effect on design gross weight, cruise altitude has a somewhat lesser effect. Hovering duration, at least for the times considered (from 1 to 10 minutes), has the least effect on design gross weight.

The combined effect of the various performance variables are best summarized graphically and are presented in Figures 22 and 23. Detailed information concerning this study is reported in Reference (3).

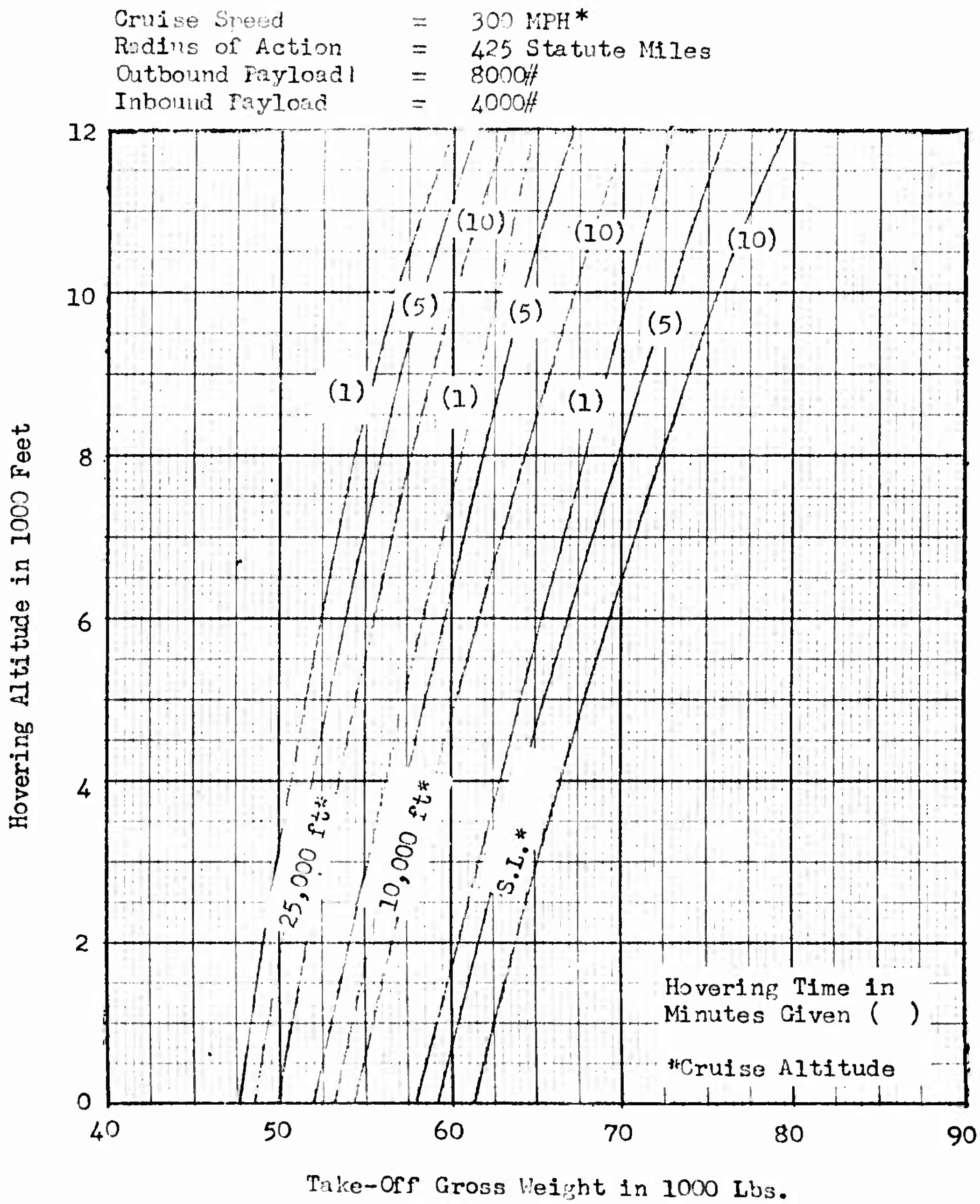
F. Transition Analysis of the Vertodyne

In Reference (10), a preliminary analysis of transition was undertaken for the Vertodyne, a VTOL turbojet driven aircraft which employs ducted fans submerged in the wings for vertical lift. These fans are driven by a turbine, powered by diverting the main jet exhaust. The analysis of the motion of this aircraft in going from the state where the weight is supported entirely by the fans, to the state as a jet propelled airplane indicated the feasibility of such a scheme, even when the propulsion system is capable only of on or off operation in supplying power to the fans. The time required and the maximum accelerations experienced in reading the normal airplane state appear to be reasonable. However, it is concluded that a more exact analysis of the problem should be performed considering in more detail, the kinematics of the Vertodyne. In addition, the study should be extended to consider the reverse transition problem which would be encountered in landing.

G. Ducted Fan Design Study of the Vertodyne

Fluid flow principles of ducted fan propulsion were reviewed and developed for several duct configurations (Reference 11). The study was based on a review of all available literature and current development work on the subject of ducted fans. Discussions were conducted with personnel of the Langley Aeronautical Laboratory, the University of Wichita and with Prof. H. H. Helmfold of Fairchild Aircraft Division.

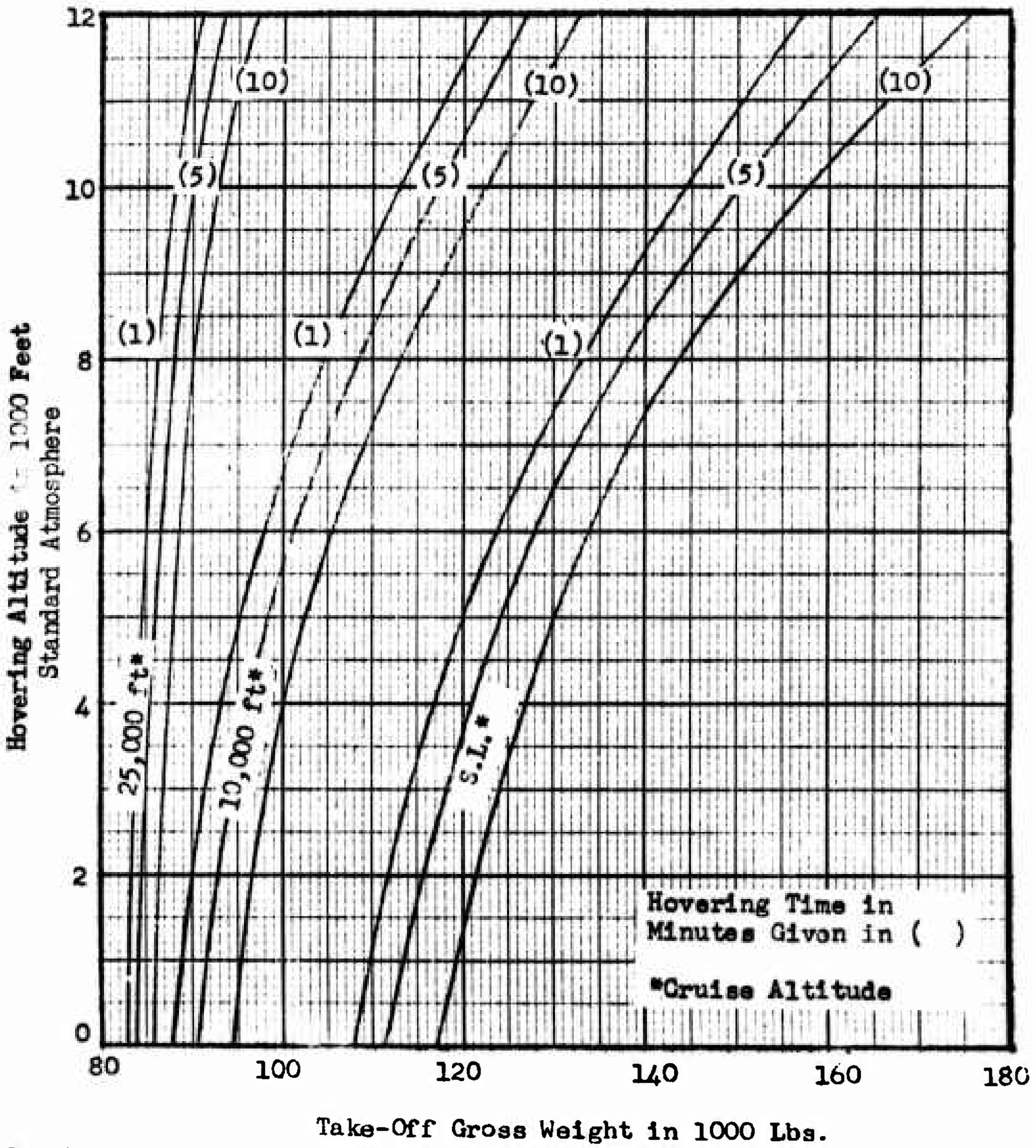
FIG. 22 - TILT WING
EFFECT OF HOVERING CEILING ON TAKE-OFF GROSS WEIGHT
STANDARD ATMOSPHERE



* Cruise Speed Approximately optimum.

FIG. 23 - VERTODYNE
EFFECT OF HOVERING CEILING ON TAKE-OFF GROSS WEIGHT
STANDARD ATMOSPHERE

Cruise Speed	=	450 MPH*
Radius of Action	=	425 Statute Miles
Outbound Payload	=	8000#
Inbound Payload	=	4000#



* Cruise Speed is not necessarily optimum but indicative of capability.

The momentum considerations of the propulsion possibilities of a fluid being pumped through a duct were developed. The relationship between the fan (or propeller) required for such pumping and the duct configuration were shown on the basis of flow pressure losses. As shown in Figure 24, a duct configuration having a flow pressure loss on the order of 25% of the exit velocity head may provide no greater thrust per horsepower than a free propeller of equal diameter.

Specifically for the Vertodyne transport configuration, a fan based on a perfect inlet bellmouth and no downstream diffusion was designed. Two dimensional cascade test data obtained by the NACA was used in the design of the fan blading. The hovering (static thrust) output of the ducted fan (at 6,000', 95°F) was estimated to be 2.7 pounds of thrust per horsepower; however, the gains to be expected from decreased disc loading or downstream diffusion are clearly shown in Figure 25. The maximum considered configuration resulting in 5.5 pounds of thrust per horsepower. Thrust control by means of inlet guide vanes was studied. A thrust reduction of 30% appears feasible at fixed RPM. Additional cascade information at low inlet angles is necessary to evaluate the ability to obtain the required inlet vane turning angles.

The following conclusions and recommendations were presented:

1. The propulsion ability of a ducted fan may be predicted by momentum and flow pressure loss considerations of the duct.

2. The fan design may be based on the required flow velocities pressure plus the duct pressure losses.

3. Further test information should be obtained:

   a. Pertinent cascade data approaching 0° and 90° β.

   b. Ducted Fan Tests

      1. The performance of a fan or propeller "in" or "out" of a duct or shroud should not be determined. A specific fan is required for one case and may be completely off-design for the other.

FIG. 24 - VARIATION IN THRUST PER HORSEPOWER WITH DIFFUSION RATIO FOR SEVERAL INLET LOSS CONFIGURATIONS

$T = 56{,}000\#$ $w = 291.7\#/ft^2$

$A_F = 192\ ft^2$ $\rho = 0.00178\ slugs/ft^3$

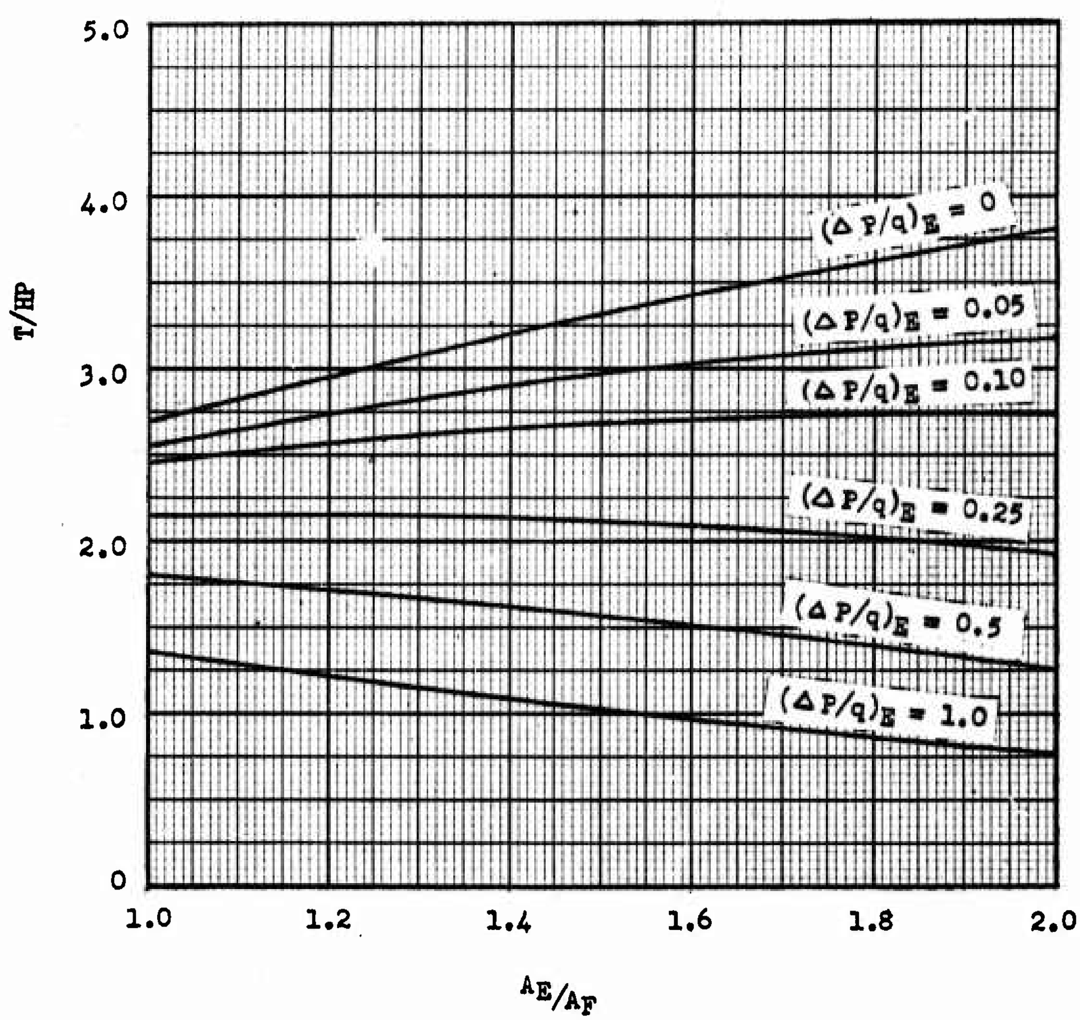
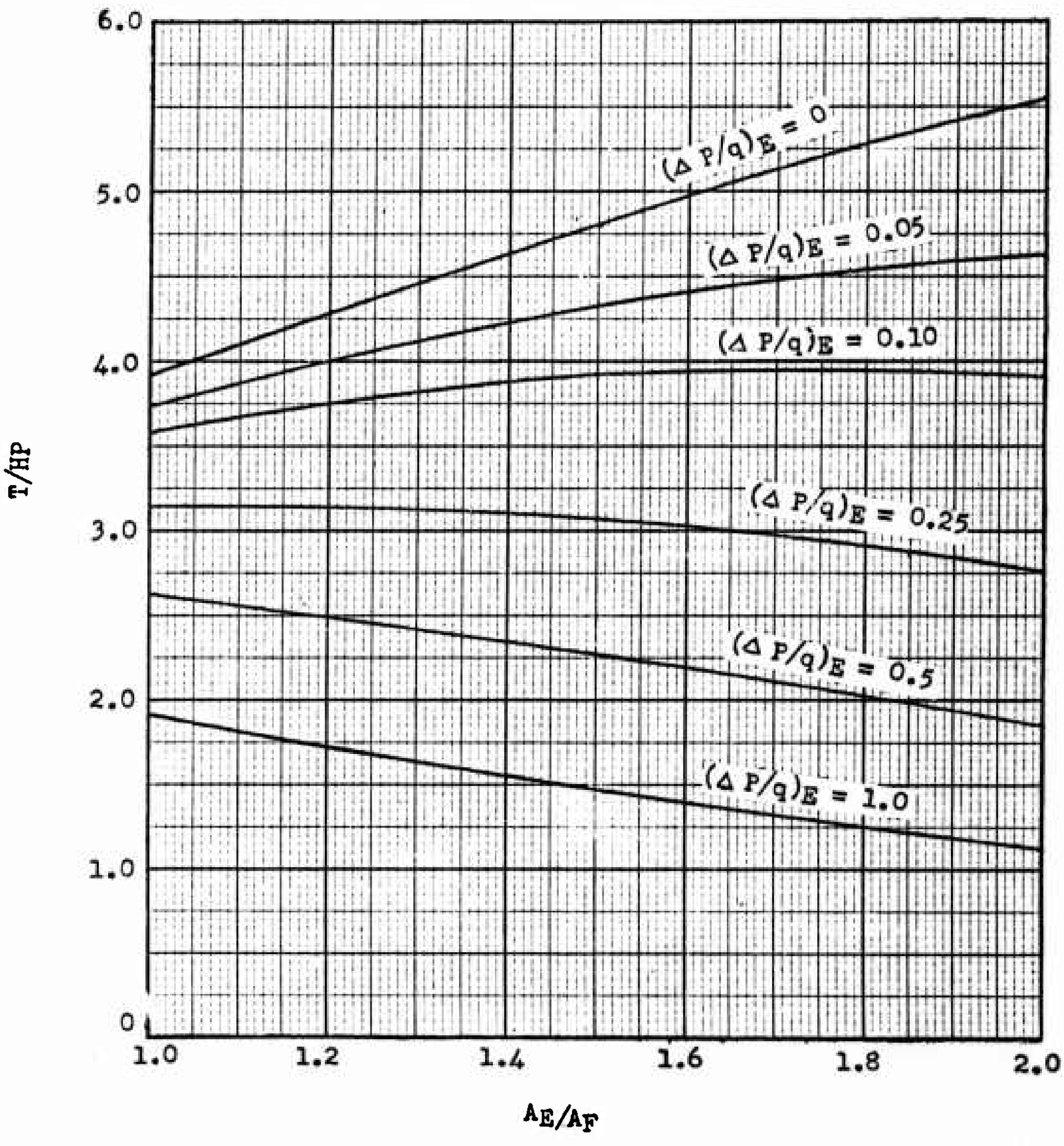


FIG. 25 - VARIATION IN THRUST PER HORSEPOWER WITH DIFFUSION RATIO FOR SEVERAL INLET LOSS CONFIGURATIONS

T = 56,000#   w = 140#/ft^2

A_F = 400 ft^2 ρ = 0.00178 slugs/ft^3



2. A test procedure for ducted fans should be developed on the basis of component testing. Various duct configurations should be evaluated separately before the complete unit is tested.

V. CONCLUSIONS

From the results of the broad comparative study and the more detailed design studies, it is concluded that the following six configurations are suitable for fulfilling the mission requirements:

1. Tilt-Wing Propeller
2. Tilting Ducted Propeller
3. Vectored-Lift
4. Special Hovering Turbojet
5. Vertodyne
6. Vectodyne

The Tilt Wing Propeller and Tilting Ducted Propeller seem to be the optimum concepts for performing the specified mission at cruising speeds of 300 mph or slightly higher. The Vectored Lift concept shows a higher gross weight for the mission because of its inherently lower efficiency in the utilization of propeller thrust for lift generation. However, only actual flight experience may show whether this drawback will not be compensated by some design or operational advantages.

For higher cruising speeds of say 400 mph and higher, the Special Hovering Turbojet and the Vertodyne become very attractive. However, the Vertodyne seems to indicate some advantage over the pure jet as it eliminates the problems of hot exhaust gases blasting against the ground and shows better characteristics in fuel consumption in hovering and near hovering flights. Both of these concepts can probably be made operationally available in the period of time similar to those of the Tilt Wing and Tilting Ducted Propeller.

Of all the six most promising concepts, the Vectodyne incorporates the largest amount of basic assemblies and parts whose weight trends and general performance cannot be established on the basis of statistical data. Because of the lack of this data, the design analysis of this type could not be as thorough as that of other aircraft, and more work is required to determine with certainty its competitive position with respect to the other most promising concepts. This absence of practical experience with many assemblies forming the Vectodyne concept may serve as an indication that this type of aircraft will probably require the longest time of development before it becomes operationally acceptable.

VI. LIST OF SYMBOLS

AR	=	aspect ratio = b^2/S
b	=	wing span, ft.; number of blades per rotor
b_p	=	number of propellers; number of rotors
C_1	=	non-bending material factor = .024
C_L	=	average rotor lift coefficient = $6 \epsilon \omega / \rho V_t^2 \sigma$
C_{L_W}	=	operational wing lift coefficient = W/qS
$C_{L_{max}}$	=	maximum lift coefficient
HP	=	horsepower
HP_P	=	propeller horsepower
HP_S	=	horsepower transmitted in the shaft
HP_X	=	horsepower transmitted in the transmission
K	=	Weight trend correlation factor
L	=	range, ft.; length of shaft or fuselage, ft.
L.F.	=	load factor
N	=	number of transmissions and/or nacelles
R	=	rotor or propeller radius, ft.
S	=	wing area, sq. ft.
SFC	=	specific fuel consumption
S_F	=	fuselage wetted area, sq. ft.
S_S	=	shroud surface area, sq. ft.
TF	=	wing taper factor
V_t	=	rotor or propeller tip speed, ft/sec.
W	=	gross weight, lbs.

W_B = blade weight, lbs.

W_{CR} = cruise fuel weight, lbs.

W_D = drive system weight, lbs.

$W_{eng.}$ = installed engine weight, lbs.

W_F = body weight, lbs.

W_{FP} = flapping propeller weight, lbs.

W_{ful} = fixed useful load, lbs.

W_L = lift propulsive system weight, lbs.

W_{LG} = landing gear weight, lbs.

W_P = propeller or propulsive group weight, lbs.

W_{SX} = synchronizing transmission, lbs.

W_T = tail weight, lbs.

σ = rotor solidity = $bcR/\pi R^2$

ω = disc loading, lbs/sq.ft. = $W/i\pi R^2$

ω_B = blade loading, lbs/sq.ft. = $W/i\sigma\pi R^2$

ω_{eng} = specific weight of engine, lbs/HP or lbs/thrust

Ω = propeller or rotor rpm

Ω_s = shaft rpm

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